Engineering Project Proposal

Toppling, Flattening, and Printing Carbon Nanotube Dominos

Final Report

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EXECUTIVE SUMMARY

Carbon nanotubes (CNTs) are long molecules having exceptional properties, including several times the strength of steel piano wire at one-fifth the density, at least five times the thermal conductivity of pure copper, and high electrical conductivity and current-carrying capacity. Among many compelling applications of CNTs, horizontal ‘ribbons’ of dense aligned CNTs are a potentially disruptive technology for use in next-generation microelectronic and micromechanical devices. [1]

CNTs are efficiently grown in a process of chemical vapor deposition (CVD) as vertically aligned 'forests' from arrays of catalyst nanoparticles on a silicon wafer. These forests are commonly grown with billions of CNTs/cm^2, but this is still below a packing density required for relevant applications. The University of Michigan Lab can produce vertically-grown CNT 'dominos', which are an array of CNT forests up to 2mm tall, with a base area of up to 1x5mm. Our goal is to transform the CNT dominos to a horizontally aligned position, condense them fifty times, and to transfer the toppled and condensed dominos to other substrates. It is also desirable to be able to transfer the processed CNTs to the same substrate while maintaining their preprocessed pattern. Our team will work with Prof. John Hart and Sameh Tawfick to design and create a process for accomplishing these objectives.

Through the course of the semester, we generated a series of concepts, ran several bench-level experiments, and discussed in detail ideas and challenges with Sameh Tawfick and Professor John Hart. We identified our two best system-level concepts and further defined individual responsibilities in order to meet our ambitious deadlines. The two concepts are a toppler method, as shown in Figure 9, p. 13, and the given roller method, shown in Figure 2, p. 7. Refer to the Bench Level Experiments section on page 10 for more detailed information on our lab preliminary lab results, and Revised Concept Selections on page 12 for a detailed introduction to the two selected concepts.

The design for our selected final concept can be seen in Figure 17, p. 18. We decided to focus our final design on the roller concept that was previous experimented with by Sameh Tawfick. This design showed the most promise in achieving the customer requirements to flatten, topple, condense, and transfer the CNT dominos. In addition to the roller, we also decided to integrate an adjustable toppler into our final design that can be easily attached and removed.

The final concept prototype holds a silicon substrate of CNTs with a sufficient vacuum force. A roller is then aligned with the CNTs visually using a simple camera. This roller is then driven over the CNTs, toppling them in this process. After this they are flattened by a simple stamping process. Finally, the roller used to knock over the CNTs is substituted for one made with a PDMS coating which can be used to pick up and print the processed CNTs where necessary.

In order to build the prototype we took advantage of many high precision parts that were purchased from Velmex.

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1 INTRODUCTION/BACKGROUND

Carbon nanotubes (CNTs) have emerged in recent years as a material with great potential in many mechanical and electrical applications. Today, CNTs are typically grown by chemical vapor deposition (CVD) onto a silicon substrate. The problem with this method is that the CNTs are not very useful once they are grown in this vertical state. The nanotubes are extremely thin and fragile because they are nearly 1 million times taller than they are thick. Our goal was to create a mechanical device to process these CNTs into more useful condition for potential applications in the future. Our team designed a machine prototype that is capable to both flatten the nanotube dominos, as well as condense them. In addition to flattening and condensing the CNTs, we designed our prototype to print them onto a different substrate. When knocking over these CVD grown CNTs, we knew that adhesion strength is very important to consider. With our machine we hope to be able to take advantage of the enormous potential in stiffness and conductivity that the carbon nanotubes can yield.

2 CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

The three most important customer requirements that we were require to meet were: flattening the CNTs, condensing the CNTs, and transferring the CNTs to another media. Our goal was to transform the vertical CNTs to be perfectly horizontal (0 degrees), to condense the CNTs to 50x their original density, and to optionally transfer the CNTs onto a secondary substrate.

After receiving feedback on our Design Review 1 report we changed the weight on a few of our customer demanded qualities. We determined that the durability, as well as the ability to tune the densification on our mechanism were both required features. This change can be seen in our modified QFD in Appendix A, P. 41. This change did not result in a change in the most important quality characteristics in our QFD. The most important characteristic that we needed to consider was tight tolerances. The next two most important characteristics did change however. The need for automated precision control surpassed that of the need for precision chip mounting, but only by a very small amount, because our sponsor, Sameh, already manufactured a rolling device which can be controlled manually; therefore, he requested to have a mechanism that could be controlled by computer, instead of a larger version of what he already developed.

Through talking with our sponsor we also determined that it is desirable to keep our CNTs on the original substrate and not only transfer onto a secondary substrate. This affected some of our preliminary concepts because they were mostly based on an assumed desired transfer of the CNTs onto another substrate.

We also updated a few of our engineering specifications. We were told that our placement tolerance for our processed CNTs is ± 10µm, which means the transferred CNTs should be within a 10µm circle from the original position. This means that our CNTs needed to be within this tolerance on either the secondary substrate, or the original substrate.

Table 1, p.5 illustrates the customer requirements, their corresponding engineering specifications, and target values.

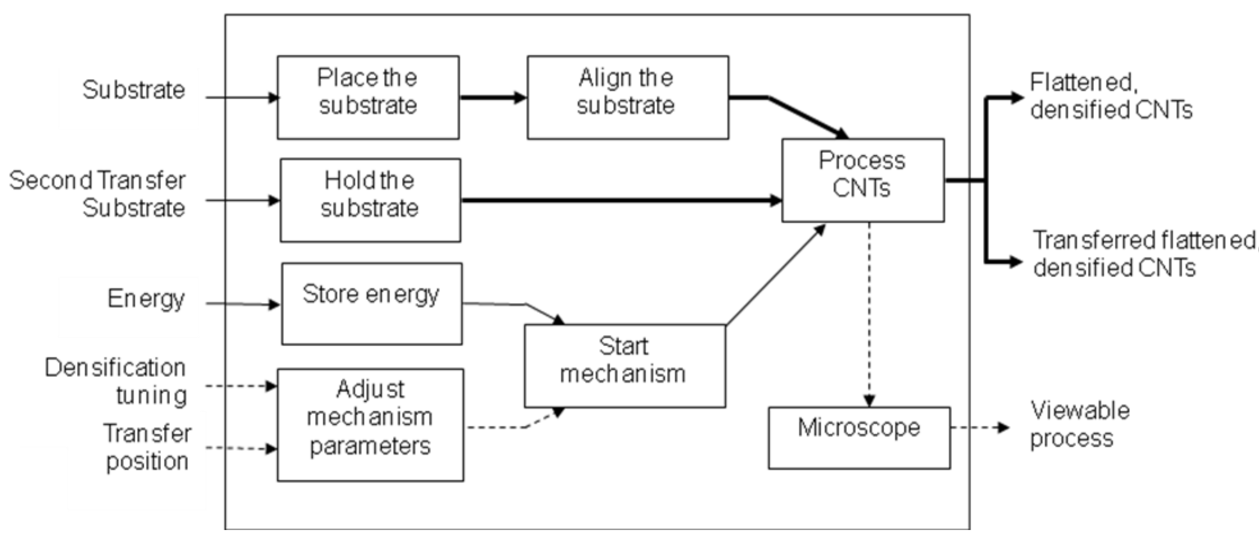
Table 1. Customer Requirements, Engineering Specifications, and Target Values

Customer requirement	Engineering Specification	Target Value
Flatten CNTs	Angle (degrees)	0
Condense CNTs	Density	50 times greater
Precise alignment	Angle(degrees)	±1□
Uniform densification	Height(microns)	±10%
Visible process	Visible(Boolean)	true
Repeatable process	Lifetime (years)	5 years
Transfer aligned CNTs to other media	Percentage of CNTs (%)	>90
Provide a means to tune the densification	Range of forces(N)	1 to 50 N
Easy to use	Number of Steps(#)	<10
Upgradable	Upgradable(Boolean)	true
Low cost	Cost($)	< $5,000
Portable	Weight (Pounds)	< 10
Durable	lifetime (years)	5

3 PROBLEM DECOMPOSITION

We decomposed the functions of our final designs into inputs, processing modules and outputs as shown below in Figure 1. We input the substrate, energy and some adjust mechanism parameters such as densification tuning and transfer position to the device. It would then align the substrates to the desired positions and process the CNTs according to the specific mechanism parameters. Output would be either the flattened, condensed CNTs on the original substrate or transferred to a secondary substrate. A microscope could also be used to monitor the process.

Figure 1. Functional Decomposition



4 CONCEPT GENERATION PROCESS

For our concept generation we first brainstormed ideas as a team, after which we decided to have each team member come up with five different concepts to present to the team. Initially, we had trouble moving beyond the rolling concept idea. Also thinking about the concepts on the small scale also made it difficult. We decided that developing more innovative concepts would require us to look beyond the rolling concept and to not dismiss ideas outright because they did not seem capable at the nanoscale.

We revisited the brainstorming stage and decided we wanted each other to come up with more varied concepts. We then broke up individually and allowed everyone a few days to think about different concept ideas. Once we had an idea, we sketched it out on a plain white piece of paper. These sketches were crude, but they conveyed the main idea clearly.

After we had all of our concept ideas drawn out, we met with our sponsor to go over them in more detail. We started by grouping similar concepts from different individuals. Our sponsor, Sameh Tawfick helped us evaluate each concept for feasibility. We did this by going through our list of customer requirements and determining how difficult each requirement would be to meet with each separate concept.

This analysis resulted in a Pugh chart shown in Table 2, p. 10 the Concept Selection section. This chart allowed us to compare the concepts we had come up with against our reference: the roller concept. We rated each customer requirement as being easier, harder, or just as difficult to meet. Easier was denoted with a plus (+), harder with a minus (-), and just as difficult with a zero (0). We scored the plusses as +1, the minuses as -1, and the zeros as 0. Each column was added up to come up with a total score for each concept.

In the end we found that our squeezer and airplane concepts were just as promising as the roller concept, but we understood that it was just a preliminary testing result, a more detailed measurement would be considered in the later discussion. Both of these concepts ended up with a score of 0, meaning that we felt they could be just as effective as the rolling concept.

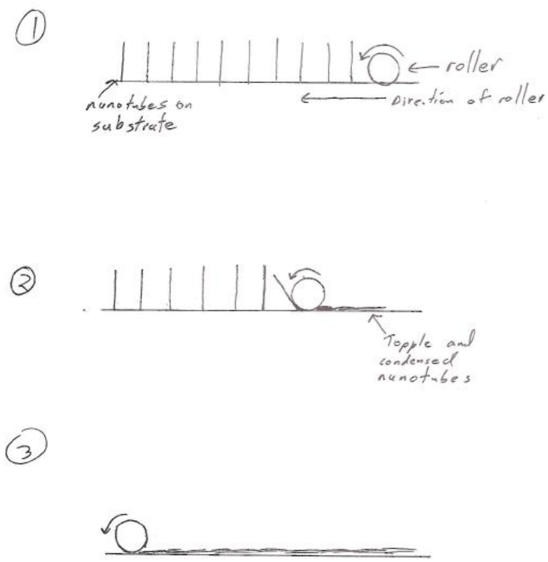
4.1 Concepts

The following section summarizes each different concept that our team came up with during our brainstorming. Using the concept selection matrix on page 10, we narrowed our ideas down to a roller, squeezer, and an airplane concept. We decided to include the pictures of these concepts in their respective sections. The pictures of the remaining concepts we generated can be found in Appendix B, p. 42.

4.1.1 Roller

The roller concept is our reference concept that was developed by Sameh Tawfick. This process uses a small cylindrical pin that rolls over the nanotubes. This motion allows the nanotubes to topple and be crushed by the roller. The ability to transfer the nanotubes would be accomplished either by printing them during the rolling process or stamping them after the rolling has been completed.

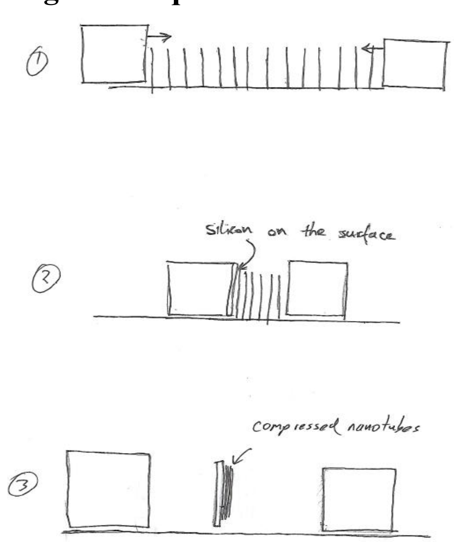
Figure 2. Roller Method



4.1.2 Squeezer

The squeezer concept involves the use of two surfaces that are aligned vertically with the substrate. One or both vertically surfaces are moved across the substrate to shear the nanotubes from the catalyst holding them to the substrate. The nanotubes are then moved across the substrate until both vertical surfaces come in contact allowing the nanotubes to be compressed. For the transfer, one of the vertical surfaces could be a second substrate that the nanotubes would stick to after they are compressed.

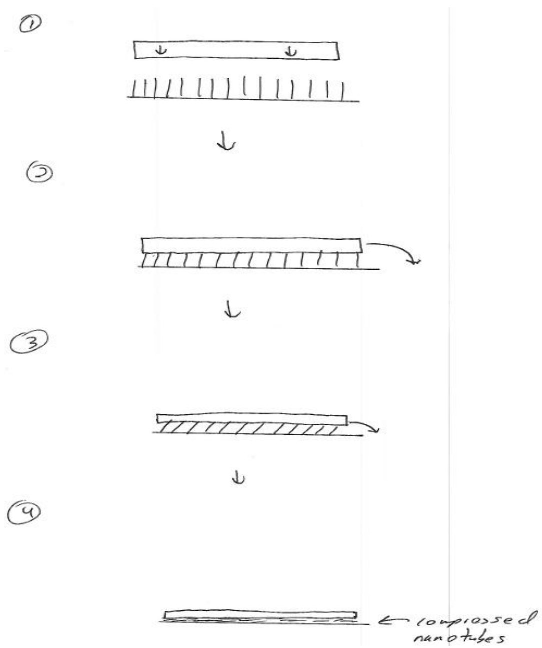
Figure 3. Squeezer Method



4.1.3 Airplane

The airplane concept would have a flat surface come in contact with the top of the nanotubes. Once this surface has made contact it is then moved in a desired radial direction to topple the nanotubes. The same surface is used to compress the nanotubes once they are toppled, and may also act as the second substrate that the nanotubes are transferred.

Figure 4. Airplane Method



4.1.4 Break Catalyst and Topple

This concept would use a gas or liquid substance that is capable of dissolving the catalyst holding the nanotubes to the substrate. Once the catalyst is dissolved, the substrate would be oriented in the direction the tubes are to fall. The tubes could fall either by gravitational force or by using an ultrasonic vibration. Finally, they would be crushed and printed using a stamping process after they have fallen horizontally. See Appendix B, p. 42 for illustrations of this and all following concepts.

4.1.5 Magnet

The magnet concept would involve coating the nanotubes with a magnetized material. This would allow the nanotubes to be attracted to an electromagnetic surface. Once the nanotubes are on the magnetic surface the magnet would be moved to the secondary substrate and compress the nanotubes. After the compression is completed the electromagnet would be turned off and leave the compressed nanotubes on the second substrate.

4.1.6 Tweezer

The tweezer concept would utilize a mechanism that has an adjustable gripper that is capable of grabbing the nanotube dominos. This mechanism would grab each nanotube like a tweezer and move them to a secondary substrate. Once all the nanotubes have been moved onto the second substrate they would be compressed by a stamping process.

4.1.7 Hinge

The hinge method would use a hinged device that is moved to the edge of each nanotube domino and would then topple the domino horizontally and crush it. The hinge device would then move on the next domino and repeat this process until all the nanotubes are toppled and crushed.

4.1.8 Wedge Crusher

The wedge crusher concept would have a device that comes down on the nanotubes to crush them. The device would have a wedged surface that comes approaches the nanotubes at an angle. This angle is necessary so the nanotubes are not crushed but instead are forced to topple in the angle direction.

4.2 Concept Selection

We used a concept selection matrix, verified by our sponsors, to help determine the most promising concepts. The matrix compares each of our ideas to the roller concept in each of the customer requirements. We were able to fill in the matrix through discussions with Sameh regarding his success with the rolling concept, the properties of the CNT dominos and his opinion of the nanotubes' interaction with the concept, and our limited observation and experience in the lab. The possible ratings are equal, better, worse. Summing the scores of each concept helped to determine the more promising ideas with less personal bias. The concept selection matrix pointed to two ideas, which Sameh had previously expressed interest in, as being roughly comparable to the baseline rolling method. See Table 2, p.10 for the complete matrix.

Table 2. Concept Selection Matrix

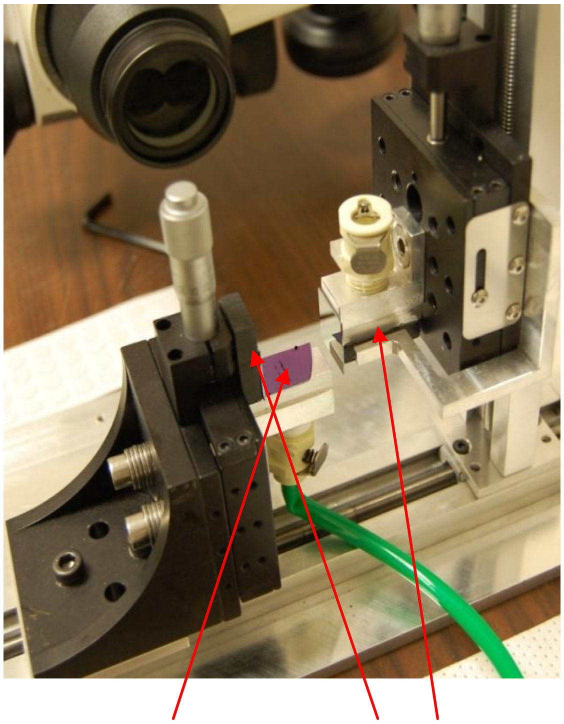
		Concepts							
		Roller (reference)	Sqeezer	Break catalyst	Magnets	Tweezer	Hinge	Airplane	Wedge crusher
Selection Criteria	flatten CNTs	0	+	0	0	0	+	+	-
	condense CNTs	0	+	0	0	-	0	+	-
	precise toppled alignment	0	-	-	-	0	0	0	-
	uniform densification	0	0	0	0	0	-	0	-
	viewable process	0	0	0	-	0	0	0	0
	repeatable process	0	-	-	-	-	+	0	0
	Topple CNTs to original substrate	0	-	0	-	-	0	0	0
	transfer aligned CNTs to other media	0	+	+	+	+	0	0	0
	Provide a means to tune the densification	0	0	0	0	0	0	0	0
	easy to use	0	0	-	-	-	+	0	+
	upgradable	0	0	0	0	0	0	0	0
	low cost	0	0	-	-	-	-	-	+
	portable	0	0	-	-	0	0	0	0
	durable	0	0	-	-	-	-	-	0
	Flexible towards incoming substrate dimensions	0	0	+	0	0	-	0	0
	Total +	0	3	2	1	1	3	2	2
	Total -	0	3	6	8	6	4	2	4
	Overall	**0**	**0**	**-4**	**-7**	**-5**	**-1**	**0**	**-2**
	Continue?	Yes	Yes	No	No	No	No	Yes	No

4.3 Bench-Level Experiments

We were only able to experiment with a limited number of CNT domino substrates, as their fabrication is time consuming and expensive. We were allotted two substrates of two domino rows each for experiment, and used these to test two of our new concepts. Using the results of our concept selection matrix, we proceeded to test the Squeezer and Airplane concepts.

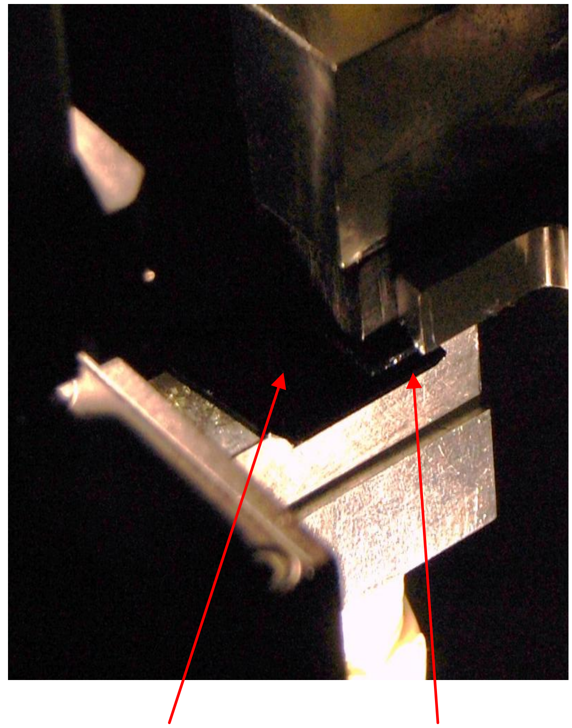
We were able to adapt Sameh's rolling test assembly for both of these concepts. Neither test would have accurate measuring and control of distance or force, but the motions would be faithful and the whole process visually monitored. Figures 5 and 6, p. 11 illustrate our test setup.

Figure 5. Squeezer Setup



CNT dominos Squeezer surfaces

Figure 6. Airplane Setup



CNT dominos Top surface

We first tested the squeezer setup. Our modification of Sameh's test method kept the substrate in the same placement as the rolling setup, but two other substrates were attached vertically on the moving jaws of the mechanism. Our first attempt resulted in the line of CNT dominos to actually topple horizontally and then stick to vertically to the edge of the moving secondary substrate. This was not the results we anticipated to get since we wanted the CNT dominos to slide across the substrate.

We modified this test by making the moving substrate approach the CNT dominos at a slight angle. This still had similar results to the first attempt. Finally we tried the original squeezer setup with a CNT domino substrate that had a weaker hold with the catalyst between the CNTs and the substrate. This weaker hold allowed the line of dominos to slide across the substrate and be compressed between the two vertically plates.

For the airplane method setup, we used a vacuum that held the CNT domino substrate in place and a secondary substrate on the moving jaw of the mechanism. The top substrate was aligned visually through the microscope until it was just touching the tops of the CNT dominos. Once aligned, the top surface was moved in a radial direction to both topple and crush the CNT dominos. The control for this setup was not precise or measured since it was just moved by hand, and the process was also hard to see visually since there were reflections on the substrate. However, the results were better than anticipated considering the poor control of the proof of concept setup, because the processed CNTs are flattened in a 90 degree angle without sticking to the toppler. The final results showed that the CNT dominos could be toppled and crushed, however some of them peeled back after the top surface was lifted.

After our second design review we completed additional bench-level testing. The concept we looked more closely at was the toppler concept shown in Figure 7 below. Using the existing device that Sameh has used for rolling we modified it for a toppling proof of concept. We modeled and fabricated two toppler configurations and were able to complete testing on two CNT domino substrates. For these tests the toppler was positioned at a 15-degree angle and raised 200 microns off the substrate. This test was successful at toppling the CNT dominos. After toppling the CNTs we crushed them with approximately 6N of force to condense them. Figure 8 below shows this process.

Figure 7. Toppler Setup

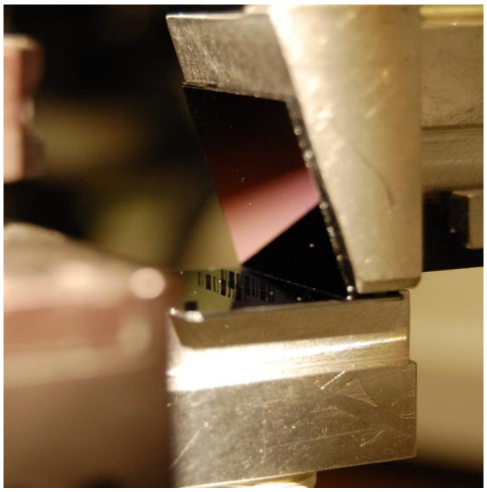
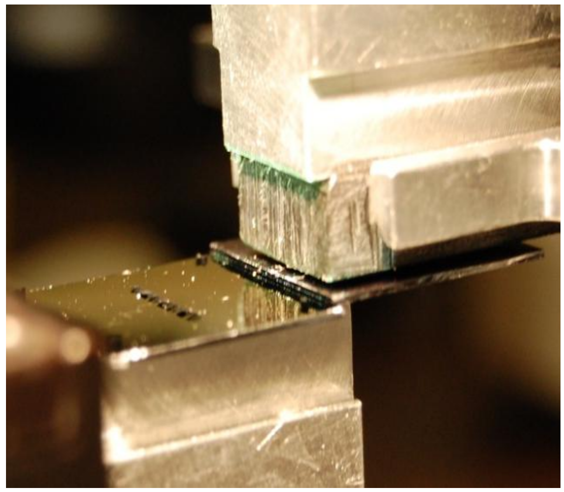


Figure 8. Flattened Dominos



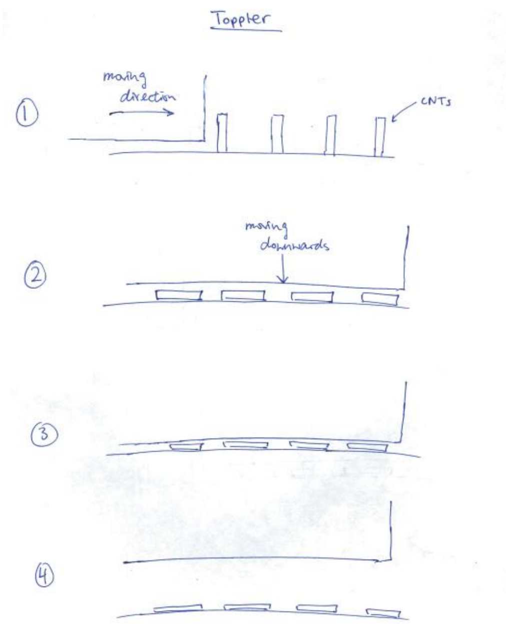
Because CNT domino substrates are expensive and not easily fabricated we did not do additional bench-level testing with the rolling method. Since Sameh had completed many tests with rolling we instead discussed the roller testing with him further. We discussed critical issues with his current design that needed to be addressed if we were to pursue the rolling concept; one major issue being unable to achieve uniformity due to the roller bending. We also reviewed some of the SEM photos from previous experiments

4.4 Revised Concept Selections

Working in the lab for the first round of bench-level testing led to a few new ideas regarding the CNT flattening. Completely unexpected, the toppling of the CNT dominos in the first failed squeeze method test revealed some potentially useful behavior. Further consideration to the airplane and squeeze method reduced their attractiveness, and this is why the result of a meeting with Professor Hart was to narrow down the concepts to two: the original roller method, and a new 'toppler' method, in which an edge or surface would be pushed into the side of the CNT dominos.

After our meeting with Professor Hart, we developed two alpha concepts: a CNT rolling machine as shown above in Figure 2, p. 7, and a CNT toppling machine. See Figure 9 below for a basic toppling machine.

Figure 9. Toppling Machine Concept



With the above toppling machine, the CNT dominos are toppled by the moment generated between an applied lateral force and their connection to the catalyst on the substrate. The toppler moves across the substrate, toppling all the dominos, and could finally flatten and condense them with a downwards motion of a smooth lower surface.

4.5 Critical Modules

Table 3. Critical Modules

Toppling Machine	Rolling Machine
Contact edge*	Roller Alignment*
Uniform force	Uniform force
Drive mechanism	Rotational speed
Squish motion and force control	Roller surface finish

*Most critical module (MCM)

4.5.1 Toppling Machine Contact Edge

The most critical module (MCM) of the toppling machine is the shape, surface and location of the contact edge. The contact edge must be optimized for the least damaging and highest quality precision toppling of the CNT domino. We created three edge shape ideas as shown below in Figures 10, 11, and 12 and used physical modeling, bench-level experiments, and manufacturing constraints to determine the best one for use in a toppling machine.

Figure 10. Square Edge

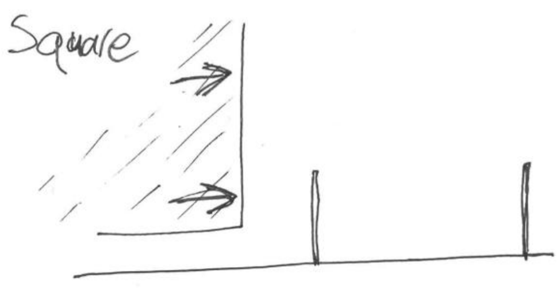


Figure 11. Round Edge

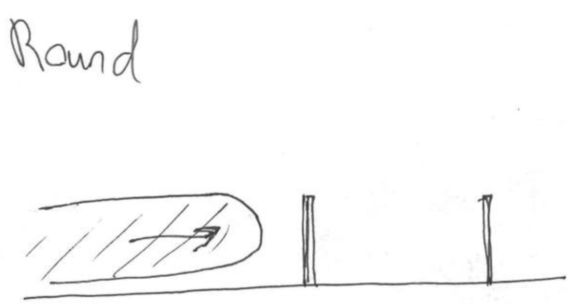
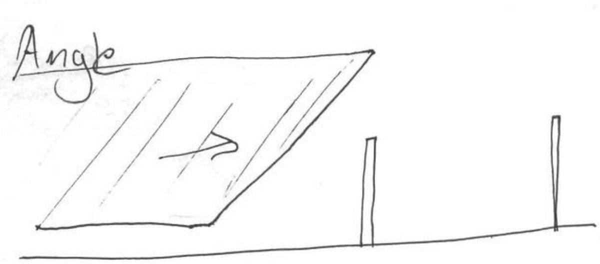


Figure 12. Angled Edge



Key challenges for leading edge selection were behavior and maneuverability. We modeled the dominos to help predict the importance of the leading edge shape, and structured bench-level tests using our modeled data and conclusions. We investigated the feasibility of manufacturing different leading contact edge topplers of sufficient accuracy on the micro scale.

4.5.2 Rolling Machine Roller Alignment

The MCM of our rolling machine is the roller alignment. Achieving and maintaining a precisely aligned roller is critical to flatten the CNT dominos evenly and accurately. We had four preliminary concepts, shown below in Figures 13-16, which illustrate roller alignment ideas.

Figure 13. Geared Roller

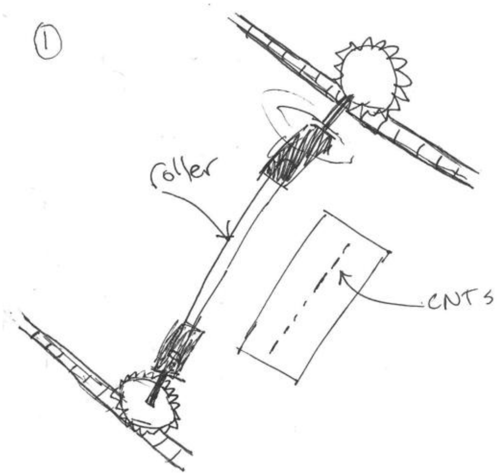


Figure 14. Align and Roll

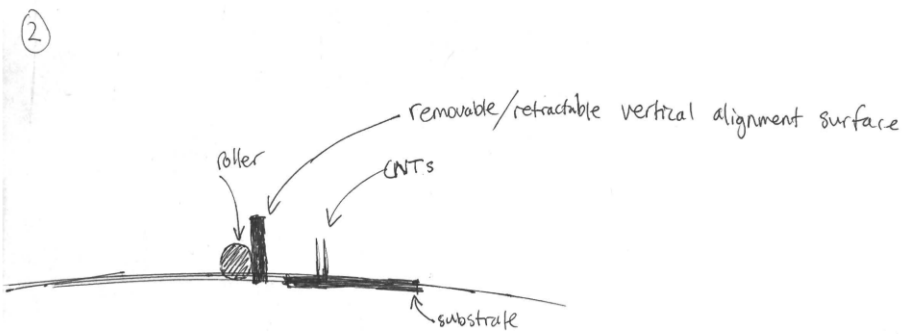


Figure 15. Linkage Alignment

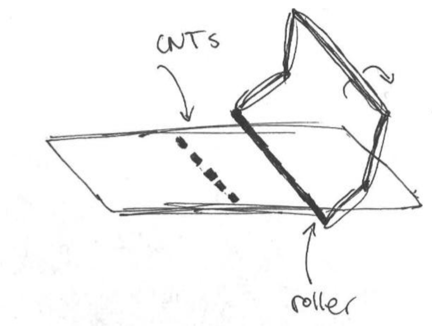
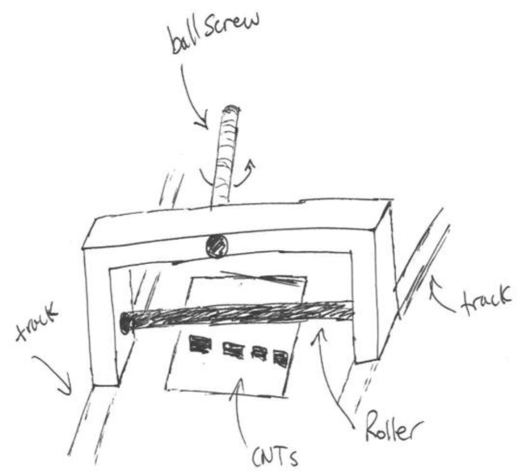


Figure 16. Ball screw and track



These concepts were not all practical, but each of their ideas could be mixed in the product design. To help choose which direction to concentrate our effort, we created Table 4, p. 17 similar to Table 2, p. 10 "Concept selection matrix." Table 4 showed the ball screw driving a tracked roller as our most promising concept, and this was further evaluated for our beta design. When it became evident the roller and substrate may need to roll with some slip ratio, a move towards independently controlled substrate linear speed and roller rotation was made.

Table 4. Roller Alignment Selection Matrix

		Concepts				
		Sandwiched Roller	Geared Roller	Align and Roll	Linkage Alignment	Ball Screw and Track
Selection Criteria	Precise Roller Alignment	0	+	+	+	+
	Controllable roller traverse	0	0	-	0	+
	Ability to control rolling pressure	0	-	0	-	+
	Rolling pressure uniformity	0	-	0	-	+
	Controllable rotational speed	0	+	-	0	0
	Total +	0	2	1	1	4
	Total -	0	2	2	2	0
	Overall	**0**	**0**	**-1**	**-1**	**4**
	Continue?	No	No	No	No	Yes

5 FINAL DESIGN

5.1 Design Description

Our final design is a rolling machine, with capability for printing, toppling, and flattening. It is shown below in a toppling configuration, with a small roller pin chucked and held under the pair of idlers. The machine has four axes of motion between the head and the substrate. The two main axes are the X and Z axis. Initially, only the lower axis will be motor controlled, but the vertical axis can accept a standard stepper motor at any future time. The Y translational and Z rotational axis are both manually operated. In addition, the roller assembly is constrained to spin, controlled by a second motor.

This machine design allows precise alignment between the roller and the CNT dominos without relying on the alignment of the dominos to the substrate. In a rolling mode, the control of the X axis and the roller angular speed allows the roller to roll without slip for any sized roller loaded, or to alternately slip at a controlled rate if desired. See Fig. 17 on page 18 for a solid view of our final design. Part details and engineering drawings are found in Appendices D and F.

Figure 17. Isometric Solid View of Final Design

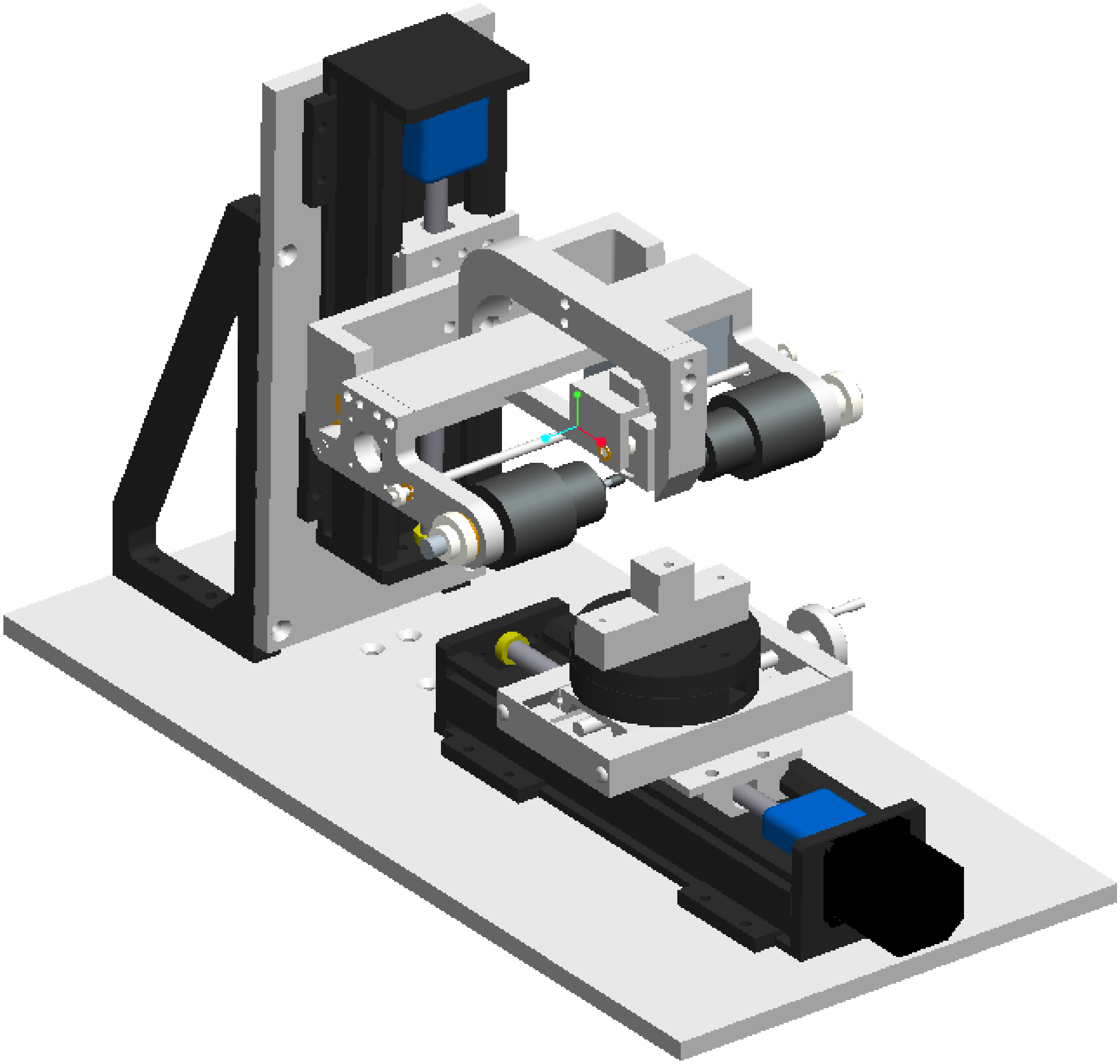


Figure 18. Cross Section of Head

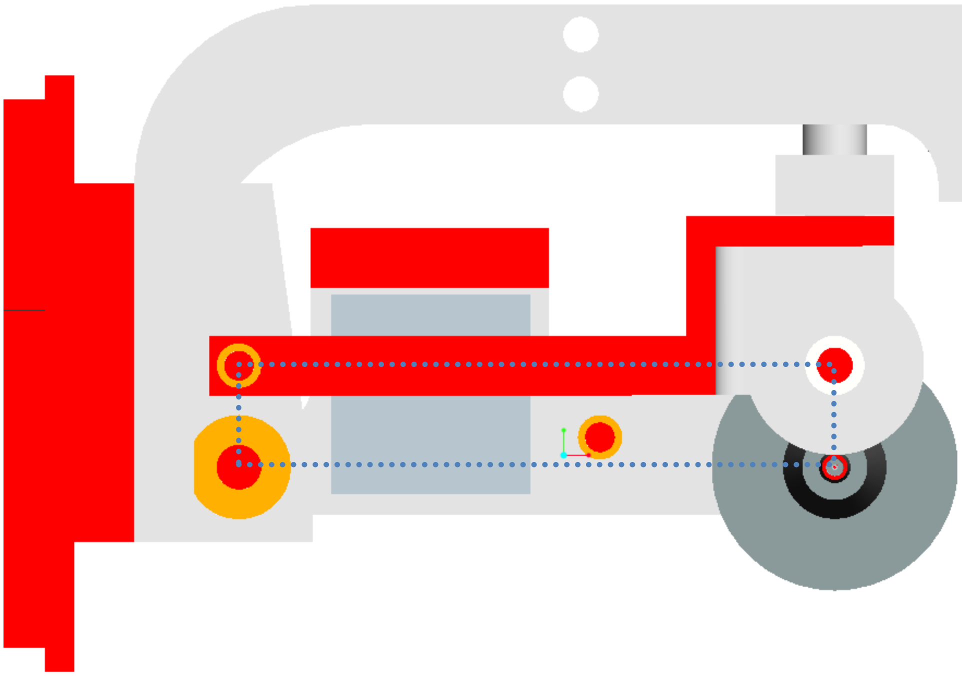
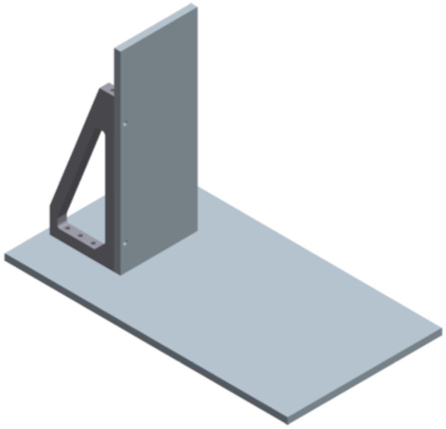


Figure 18 above shows a cross-section of the head assembly, showing the simple four-bar linkage consisting of the support wings (4.1.1), follower arm (4.4.1), idlers (4.4.3), and roller sideplates (4.3.1). The design of the head assembly will be discussed further below.

5.1.1 Chassis

The chassis is constructed of ½" 6061 aluminum, with a pair of 90 degree angle supports sourced from Thor Labs. ½" 6061 is chosen in an attempt to focus on machine stability and alignment during rolling, and the thickness helps with thread engagement for the many tapped holes which are necessary.

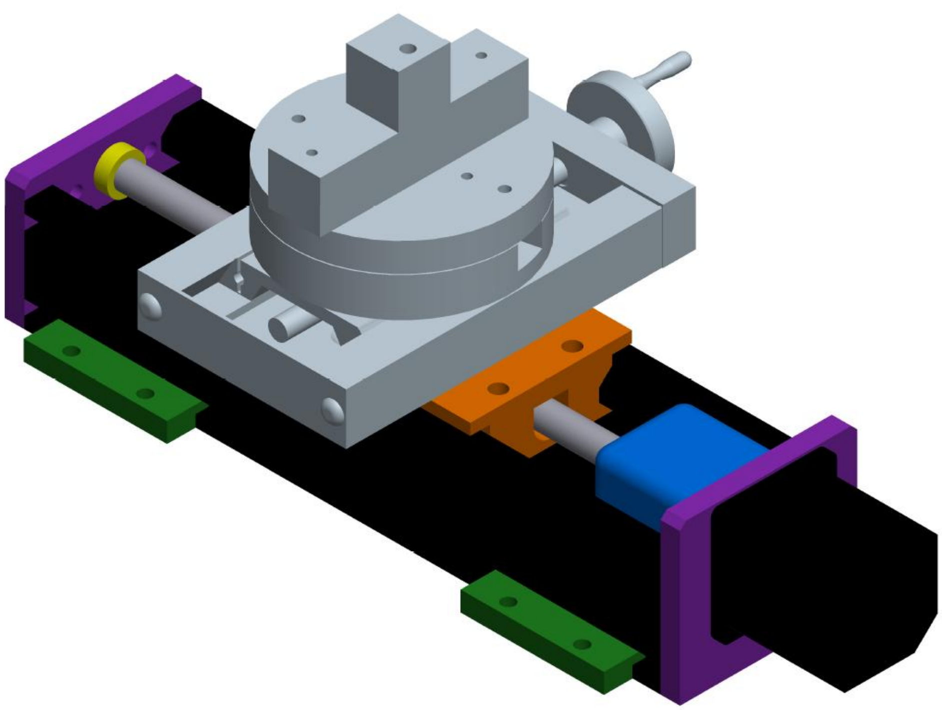
Figure 19. Chassis



5.1.2 Substrate Mount and X-Axis Assembly

The substrate is mounted on an aluminum fixture with a vacuum plug to help secure it. There is a lip towards the rear of the mount which will prevent the substrate from being sheared off the vacuum. The fixture is mounted to an X and Y translational axis, and Z rotational axis. These axes allow the CNT dominos to be aligned to the roller without relying on the dominos alignment to the substrate. The X axis is motor driven, while the rotational and Y axis is manual, and left stationary and locked once set.

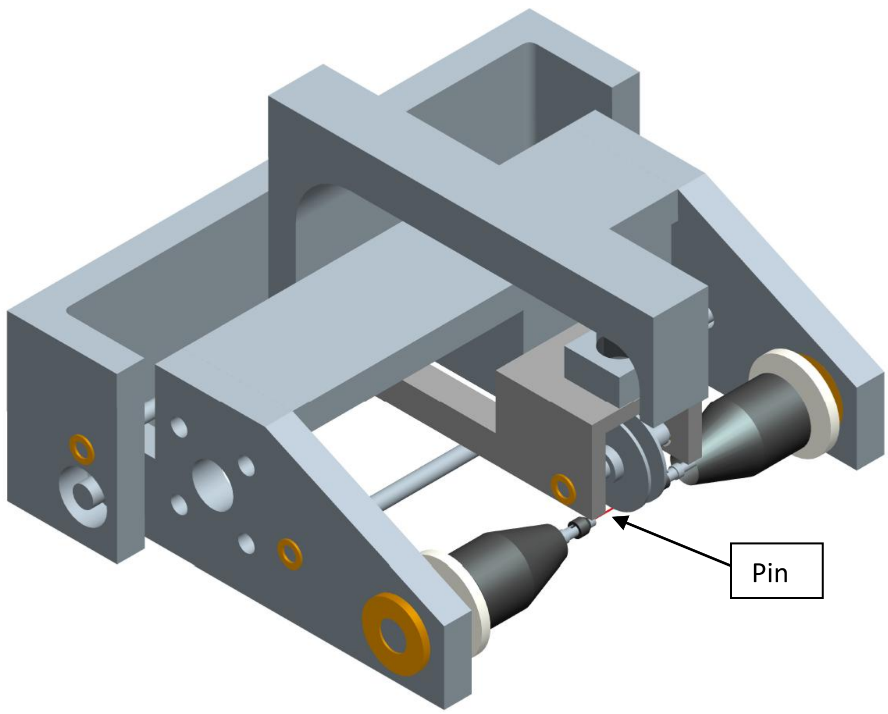
Figure 20. X-Axis Assembly



5.1.3 Machine Head

The head of the machine is attached to the Z translational axis and contains the roller, toppler, flattener, printer, compliance, and force sensor. Figure 21, p. 21 is an illustration of the machine head separate from the whole assembly.

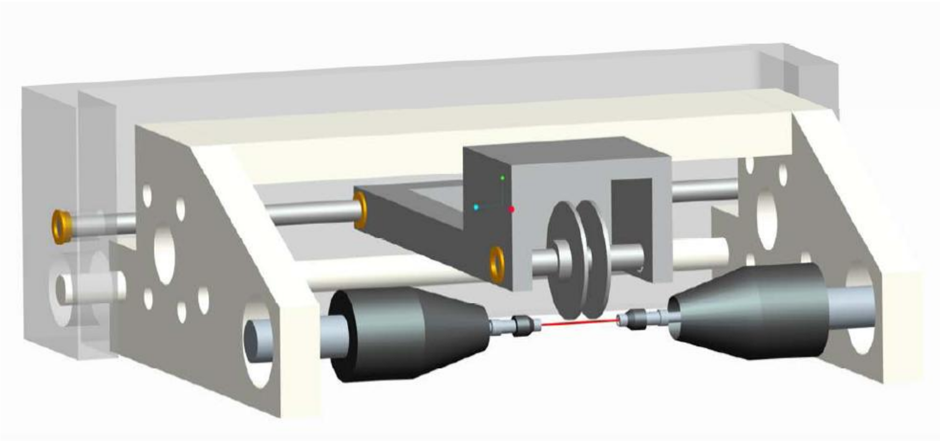
Figure 21. Machine Head in Rolling Configuration



5.1.4 Roller and Idler

The roller is shown above as the small pin captured between two wire-gauge chucks. Downward pressure is applied to the roller from the two idlers above. Both the roller and the idlers are constrained on their own arms, which pivot around separate axles towards the rear of the head. These arms are intended to constrain the motion of the roller and idler to small vertical displacements, with no other degree of freedom. This intention is approximately achieved as long as the angular displacements of the arms do not travel far from horizontal. The machine is designed to work in the ±1° range. The arms have their own pivot locations in order to allow each one to work at horizontal, and to work as a four-bar linkage and assure the roller, idler, and force sensor stay in line. See Figure 22, p. 22 for a clean view of the arms and pivot locations. The white components pivot together, the grey follower arm pivots on its own grey shaft, and both are grounded in the translucent piece in the rear of the head.

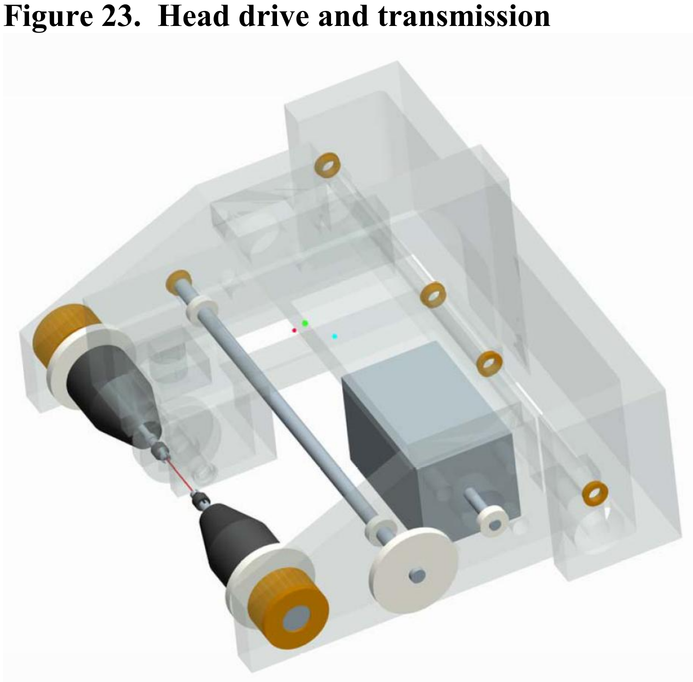
Figure 22. Illustrated roller and idler arms



The width of the roller can be adjusted by chucking the wire gauge chucks in the standard precision chucks at varying positions, and between the wire gauge chucks and standard chucks, any size roller can be used between 0.001” to 0.5” diameter. The follower idlers spin together, freely with respect to the idler, and their locations can be adjusted anywhere on the follower shaft.

The roller is rotationally constrained by a second stepper motor, and driven from both sides after an approximately 4:1 timing belt reduction. The reduction does not allow an increase in torque, as stepper motors are approximately constant-power, but it does help to smooth out the accelerations of the stepper motor as it rotates from step to step by allowing the motor to run at higher speeds. Figure 23 below illustrates the drive and transmission components.

Figure 23. Head drive and transmission



The stepper motor on the right transmits torque to the center shaft though a timing belt and pulleys. The center shaft distributes torque to both sides of the roller chucks through another timing belt and pair of pulleys. Cartridge bearings are shown as orange. There is no tension adjustment, but the center-to-center distances are chosen to enable the purchase of the exact required belt lengths.

5.1.5 Sensor and Compliance

The roller and follower are allowed to move vertically in order to accommodate different rolling stock, and also allow vertical compliance in order to maintain even pressure when rolling up and over toppling CNT dominos. The vertical compliance in conjunction with a coil spring, shown as a dark component between the upper boom and the follower, does not eliminate the changes in applied pressure, but is sufficient to avoid changes on the order of magnitude which would be present in a rigid structure. A flattened CNT domino could be as tall as 150 um, and the spring is specified to have a spring constant of 20 N/mm. This will result in a change of applied force of 3N, equal to about 10% of the expected operating force.

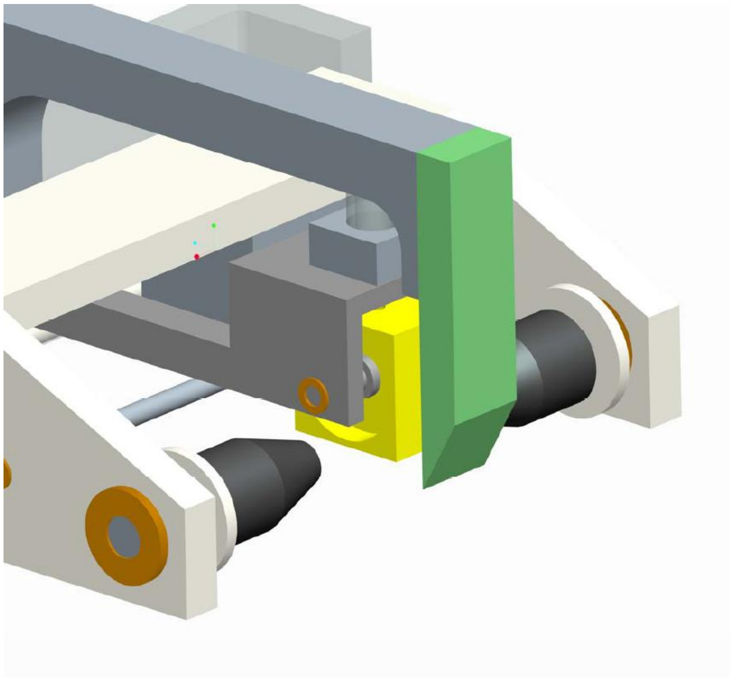
The arms are free to pivot on cartridge ball bearings. Small, low tension helper springs hold the arms up against the top boom to prevent them from hanging. As there is no moment applied at the arms' pivot locations, the entire force applied at the roller can be measured at the spring. For this reason, a force sensor is located on the underside of the boom, above the spring. The change in force measured at this sensor will be calibrated, and correspond to the force applied. The force applied is controlled by displacing the entire head with the Z axis, and compressing the spring.

5.1.6 Toppler and Flattener

The machine may be fitted with a 'toppler' as explained earlier in the paper. This toppler is a single machined piece fitted to the top boom, which extends below the roller. The shape and angle of the toppling surface was chosen as previous and machined, the vertical height is set with Z axis, and the toppler's traverse is controlled by the motorized X axis.

For use in conjunction with the toppler, or as a secondary application, the machine may be fitted with a flattener. The wire gauge chucks are removed, and the flattener attaches to the follower. The pressure applied is measured and controlled in the same manner as with the roller. See Figure 24, p. 24 for an illustration of the machine fitted with the toppler in green, and the flattener in yellow.

Figure 24. Toppler and Flattener Attached



5.1.7 Printer

The head can be fitted with a roller up to ½" diameter on either end, thereby accommodating a sufficiently large roller to span any incoming substrate. A PDMS roller could be run to test printing by kinetic adhesion, [XX] controlling its speed between the motorized X axis and rotational speed, or a more traditional adhesive roller could be employed.

5.2 Bill of Materials

Please see Appendix E, p. 51 for complete bill of materials.

5.3 Design Parameter Analysis

5.3.1 Overview

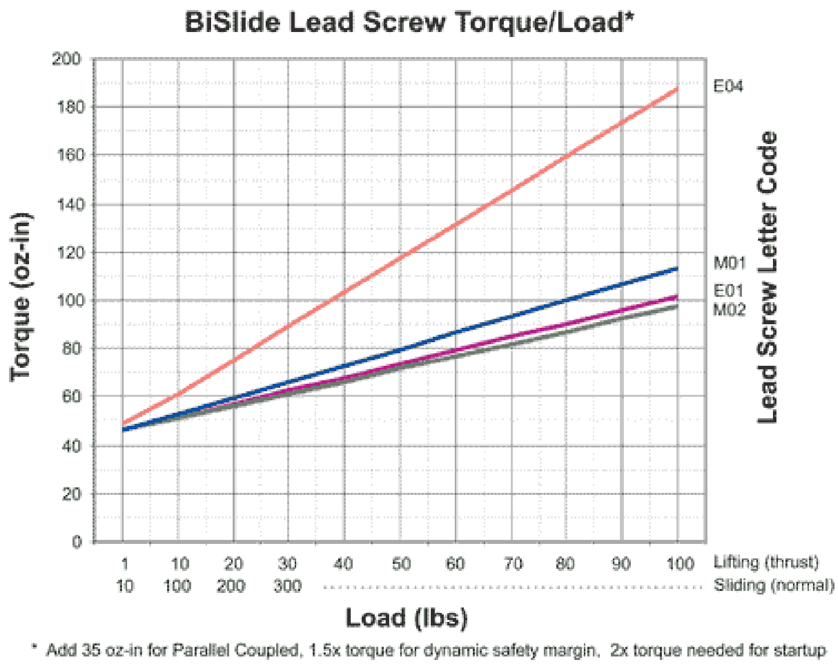
In the toppling and densification mechanism, we studied experimentally with the toppling by employing different angles of approach in order to come up with the most optimal shape of the toppler. After calculating the force distribution and running a couple bench-level tests, the results of using a toppler with a slight tilt, for instance around 15□ , are the most satisfactory because it works best for the task compared to other tilted angles.

Besides using a toppler, rolling is another promising mechanism. Similar to toppling method, the roller is the most critical tool in this rolling device, and couple analyses, such as deflection and friction, have been conducted to ensure that the roller is able to work well in the process. Those analyses are to be discussed further later.

In terms of mechanical parts of our device, the chuck motors and their corresponding transmission mechanism are our main concern as well. In order to make the roller rotate, the chucks which hold the roller at two ends need to be driven. We chose to use a stepper motor to simply ensure rotational speed. The motor model was determined by its' required torque and speed. The transmission ratio also was chosen by researching the operating range of the class of required motors and comparing this to the operating range required at the roller. After comparing our criteria with stepper motors available in the market, NEMA 17 was determined to be capable of fulfilling our requirements with a relative low cost.

Stepper motors are also to be used on the bi-slide which controls the translational location between the roller and the silicon substrate. The motor here has a fixed ratio between rotational speed and translation as determined by the bislide leadscrew pitch, and we have specified it depending on our required linear speed and thrust load, per outlined by Velmex [6] below in Figure 25.

Figure 25. Velmex Bislide Required Motor Torques



5.3.2 Properties of Roller

We first narrowed down to stainless steel pin and quartz tube to be our roller material because of their round shape, good surface finish, small cross-section areas and high yield strength. Rounded shape and good surface finish gives a smooth rolling process while maintaining a uniform densification. Since the CNTs are so small, rollers with small diameters are required to topple the dominos, so that the forces exerted from the rollers would act on the lower portion of the nanotubes, which provides a toppling motion without crushing the CNTs. Lastly, having high yield strength is also one of the criteria of the rollers because the rollers may experience bending or shearing due to the reaction force from the silicon substrate or friction, which may cause yielding to the rollers.

To determine our best roller, both stainless steel pin and quartz tube were analyzed by deflection and friction modeling. Since both materials are provided from our sponsor, Sameh Tawfick, materials properties that will be used in the analysis are already determined and can be found in Table 5.

Table 5. Dimensions of stainless steel pin and quartz tube

	Stainless Steel Pin	Quartz Tube
Radius	0.6 mm	0.25 mm
Elastic Modulus	220 Gpa	72 Gpa
Shear Strength	186 Mpa	70 Mpa
Static Friction Coefficient	0.188	0.4

5.3.2.1 Deflection Modeling

The desired roller will be pressured from the top by two bearings with the two ends fixed by aluminum chucks. The silicon wafer will be held on the mounting block, which is installed at the position in between two bearings. Therefore, there would be a roller deflection, or bump, when the roller is rolling over the substrate. From this deflection analysis, using the properties above and the estimated maximum reaction force 50N, the deflections of stainless steel pin and quartz tube are $1.02*10^{-13}$ m^4 and $3.07*10^{-15}$ m^4 respectively. (See Appendix G, p. 60 for roller deflection calculation.)

5.3.2.2 Friction Modeling

Friction force between the silicon substrate and the roller can be large when the roller is sliding on the silicon, which will also produce a shear stress that may yield the roller mechanism. In order to measure the largest friction force, or the largest shear stress, from the analysis and knowing that static friction coefficient is always larger than kinetic friction coefficient, static friction coefficient is used in the calculation instead of the kinetic coefficient, even though the roller is in motion and the kinetic coefficient should be used. After comparing the resulting shear stress with the materials' shear strength while using the determined values given in Table 5, p. 26 we determined that stainless steel pin would not yield due to its high shear strength; on the other hand, the quartz tube provided by our sponsor would have yielding. (See Appendix G, p. 61 for roller friction calculation.)

5.3.3 Camera

The desired camera needed to show a live and clear image of the relationship between the CNT dominos and the roller or toppler. It is used as a method to align the CNT dominos to the roller/toppler as well as a means to view the processing of the CNT dominos. We needed the camera placed directly above the primary substrate in order to be able to align accurately. We also needed the camera capable to view from the side to allow us to view the toppling of the CNT dominos as well as the densification. To achieve the two camera views we selected a flexible camera mount that allows the camera the move to the required positions. Finally the camera needed to work in varying lighting conditions, focus at short distances, and be able to manually focus. The other main factors in deciding on a camera included the price and the portability. We aimed to have a small relatively cheap camera under $100 with a USB computer interface. After doing some research online we decided to go with the Agent V3 generic bullet webcamera. This camera cost $60 and met all of our needs.

5.3.4 Motor Analysis

First of all, to analyze the force and torque requirements for rolling, properties of the rolling stepper motor and sliding stepper motor have to be determined. One of the criteria for the rolling motor is the provided torque. We first calculated the friction force acted on the roller, from which we computed its corresponding torque by using the equation, $\tau = r \times F$, where r is the roller radius and F is the friction force. Another criterion is the size of the motor because it has to fit in the machine. Based on these two requirements, NEMA 17 (17H118D10B) was determined to be the rolling stepper motor. For sliding stepper motor, we first narrowed down our choices to NEMA 23 and NEMA 34 because they are the only motors that are compatible with the Velmex bislide. Although NEMA 34 stepper motor is able to provide a larger torque than that of NEMA 23, after analyzing the speed requirement of this application with the motor properties as well as due to a more expensive price for NEMA 34, NEMA 23(23H118D30B) was chosen to be the sliding stepper motor.

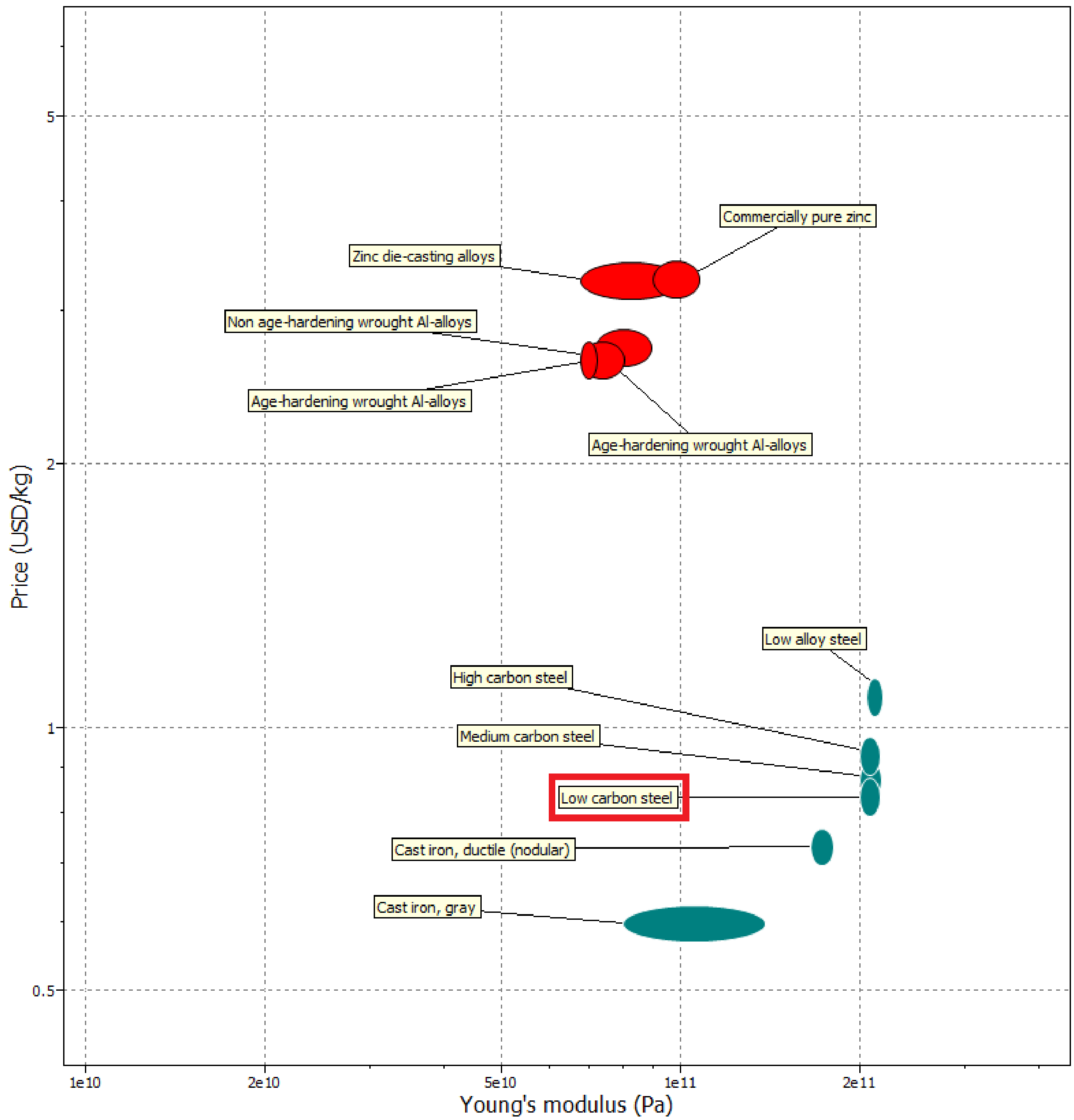
5.4 Material Selection Analysis

To determine if the necessary design requirements are met, we have done material selection analysis on both roller and vacuum chuck.

5.4.1 Roller

Since the roller is subject to a large downward force during rolling, the material selection was critical in ensuring that the roller is able to run smoothly and repeatedly. Figure 26, p. 28 shows the property table generated from the Granta CES 4.8 software for the roller. Constraints such as high degree of machinability, high yield and compression strength, as well as low cost are used as design constraints. Based on the results from CES, we determined that low carbon steel would be our best choice for the roller because of its high Young's Modulus with a relative low price.

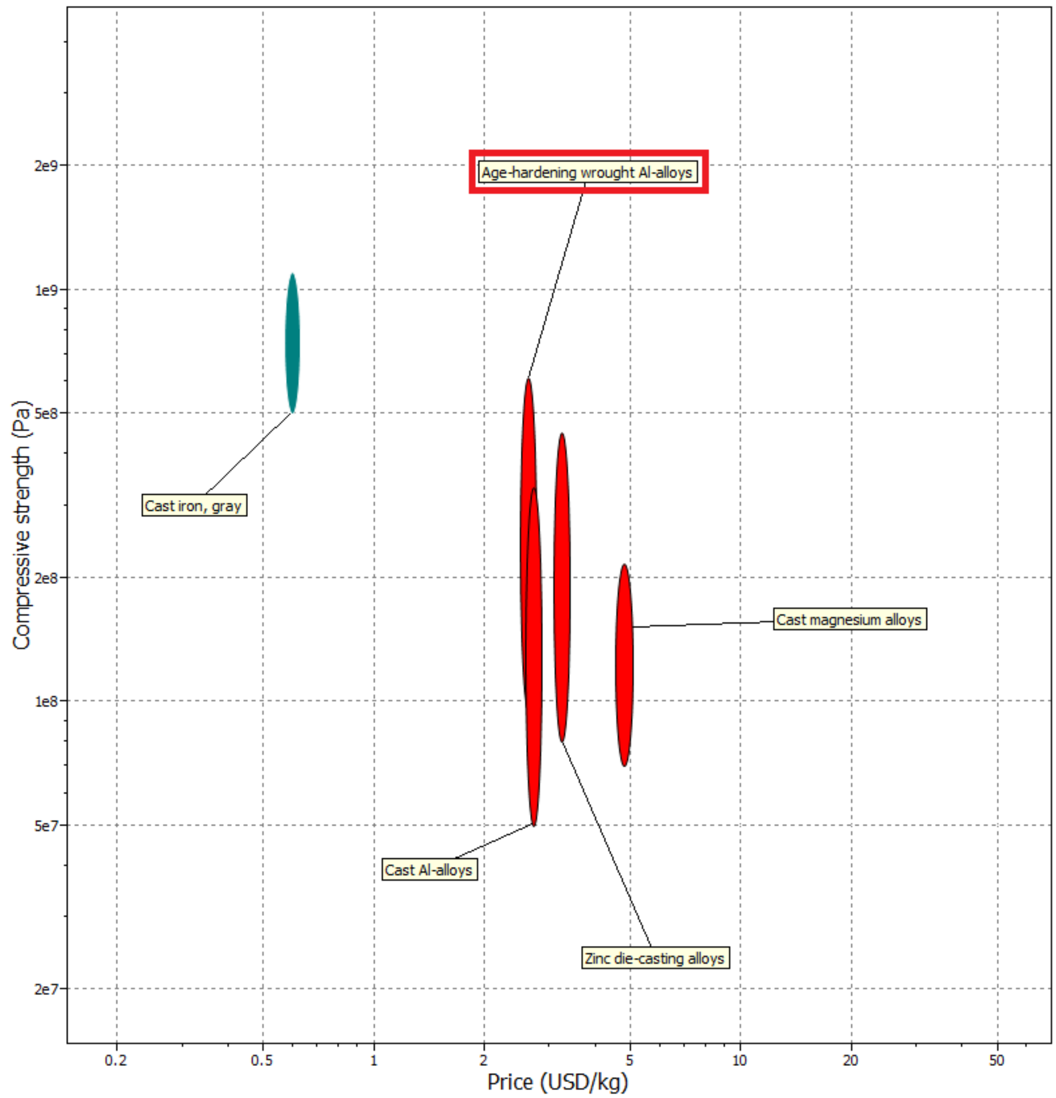
Figure 26. CES Property Table of Roller



5.4.2 Vacuum Chuck

To mount the silicon substrate during operation, the vacuum chuck needed to be able to sustain under high compressive load as well as able to be easily machinable, so that stops can be fabricated on the base plate to facilitate the mounting. Material cost was also one of our considerations in order to minimize our budget. Figure 27 shows the CES property table of the vacuum chuck, which is plotted with price against compressive strength. An age-hardening wrought aluminum alloy was determined to be the base plate material because of its high compressive strength out of all the other materials while maintaining a low price. After further consideration we chose to select 6061 aluminum as our specific material of choice. This decision was made based on the ease of manufacturing as well as the fact that 6061 aluminum was available in the most convenient size.

Figure 27. CES Property Table of Base Plate Mount



5.5 Safety and FMEA Analysis

Our design is quite small and compact and does not have many major safety hazards associated with it. We are mainly concerned about a few key problems that could occur. First, our design has a few sliding components. These components are not completely confined inside of a casing and thus could be accessed easily by a hand or finger. This is a safety concern because someone could get badly pinched if they are not paying attention and stick their hand in the way of the moving slide. One option to address this by adding a plastic shield to prevent access to this area on both slides. Another main concern is that our prototype could be operated by someone who does not know exactly how to use it. We will address this by making sure that only our group and sponsors are allowed to operate our prototype. The prototype will be closely monitored at all times while it is in use. Finally, we have some concerns with the handling of the CNTs themselves. CNTs that come into contact with and get stuck into a person's skin would likely require medical attention. This hazard can be taken care of by making sure that the primary silicon substrates should only be handled with rubber gloves. With theses safety measure in place we feel that our machine should be quite safe to use and be around.

Our machine has been designed to handle higher loads than it will experience during operation, but it still has a few possible failure modes. The stepper motor connected to the roller axis could fail due to a torque overload during printing. This problem may be addressed by making sure that this motor will only be run at safe speeds. Another possible failure mode is fatigue of the base subsystem that includes the vacuum chuck, turntable, and the x and y axis sliders. During the compression step of our CNT processing a heavy load is applied that could fatigue and bend this subsystem. With the scale we are working on it would not take much to start affecting the functionality of our prototype. We addressed this by constructing these components out of high strength aluminum so that we will have a very high safety factor against any possible yielding. Another possible failure mode is the crushing of the silicon substrate. This could occur at high loads when we are driving the z-axis bi-slide downward onto the CNTs for compression. We intend to address this by figuring out how much force we can apply to the silicon. We will then be able to add a warning into our LabVIEW program. Once the force approaches the critical value, the program could be set up to display a warning to the user. The force couldn't necessarily be limited in this case because the z-axis bi-slide is driven manually.
Using Designsafe 3.0 we have analyzed each potential hazard as well as the means to reduce the risk of each case occurring. A figure detailing these results can be found in Appendix C, p. 45.

5.6 Environmental Analysis

The environmental impact of our design concept was considered and modeled using the SimaPro software. The primary materials used in the design are 6061 Aluminum and grade 303 stainless steel. Material usage was calculated for the design based on the raw materials we ordered, and SimaPro determined the environmental impact of using the materials in the chosen amount. Table 6, p. 31 shows the environmental emissions based on the selected materials as well as the required power consumption to build the prototype. These values are also displayed in Table 6, p. 31 and Figure 28, p. 31.

Since significantly more aluminum is used, the emissions and power requirements are much greater than that of stainless steel. Thus the material with greater usage has more impact on the environment. Additional charts for the environment impact assessment are found in Appendix I, p. 63.

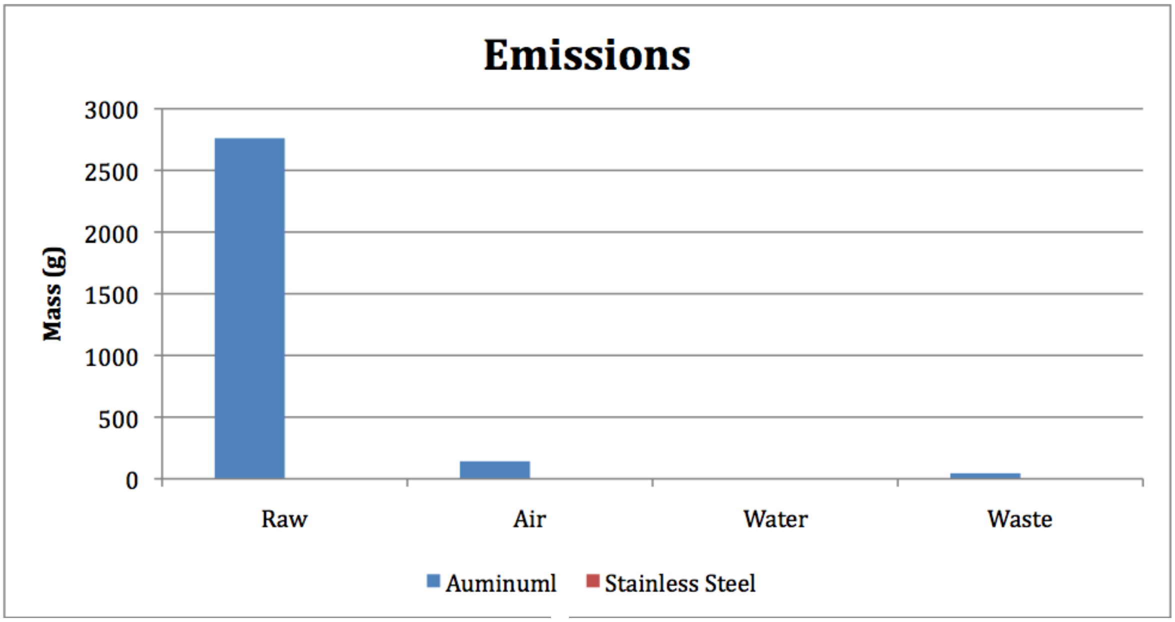
The final design has a greater impact environmental than the current state of the art design particularly in regards to power consumption and material usage. The greater power consumption is an effect of the amount of material processing, machining, and power consumption during the operation of our prototype. Power is needed as a result of the electric stepper motors that are used to drive roller and the z-axis. The current state of the art machine is entirely manually driven.

Table 6. Emissions and Power

	Emissions (g)				
	Raw	Air	Water	Waste	Total
Aluminum	2760.75	142.20	2.04	45.03133	2950.03
Stainless Steel	1.36	1.18	0.00	0.00	2.55
	2762.11	143.38	2.04	45.04	

	Power (MJ)				
	Raw	Air	Water	Waste	Total
Aluminum	457.67	716.01	-275.51	0.00	898.17
Stainless Steel	2.64	0.23	0.02	0.00	2.88
	460.31	716.24	-275.50	0.00	

Figure 28. Emissions



5.7 Manufacturing Plan

Our machine design requires many components. While many were purchased, this machine still required extensive fabrication of parts and modifications to purchase parts. Teamwork was essential to fabricate the machine on time. Just as critical as the accuracy of the individual parts, much attention was paid to the assembly of the machine, and each component connection was critically examined to maintain tight tolerances and alignment.

5.7.1 Fabrication

Our machine required the fabrication or modification of 24 components. Please see Appendix D, p. 46 for a complete component list and fabrication plan. This section will cover fabrication examples

A typical component which required modification is the 33J taper to ½" round adapter for the precision chuck. Machine tool chucks often fit to a taper for true and reliable temporary connections to drill presses and mills which they may be required on. Our tool chucks fit to a size 33 Jacob's taper. The part bought had a much longer than necessary ½" round shank, and for our machine reduced this length down using a lathe for a well-finished part.

Many aluminum plate parts, especially in the head of the machine, were rough cut on the waterjet to speed machining time. However, many components require they are held parallel by a 'T' connection between the end of a cut part and the plane of another. A common fabrication problem in this machine is that the water jet is unable to cut a perfectly vertically, as the cut is wider at the top than the bottom. The parts which require a perfectly square edge needed to be mounted in a mill and the edge needed to be finished. Another location which required finish machining was the bore of the press-fit bearings.

Some parts, like the follower arm, required they be milled out of a solid block. In the case of the follower arm, it needed to be chucked in two separate orientations in order to make all the necessary cuts, and the raw material was sized with the intention of using some extra material as a clamping point.

Finally, our machine includes many radially symmetric parts, which were fabricated on a lathe. An example of this is our idler rollers, which can be entirely fabricated on the lathe for both its shape and the internal tapping. Other parts, such as the shafts, have grooves for c-clips, or tapers for press fits machined on the lathe.

5.7.2 Assembly

Each additional part in our machine represents an opportunity to bring the alignment and parallelism of the mechanism out of specification. Our team met with Sameh [2] to discuss his experience aligning his roller mechanism, and in his experience, measures of adjustability only guarantee that the mechanism in never perfectly aligned. Therefore, we designed and assembled our mechanism without any adjustable fits, but instead using locating holes and pins parallel to the machine attachment screws where appropriate.

Each system can be assembled separately and finally connected, often at the velmex connecting plates. The one system which required care in design to allow for assembly was the head, which must be assembled in an order which allows the installation of the internal components. Like in many other aspects of the machine design, ease of disassembly is easily sacrificed for assembly tolerances.

5.8 Usability Analysis

5.8.1 Setup

To begin with, our machine needs to be set up on a flat table and needs a fair amount of light. Next, the electronics, including the alignment camera and connecting computer need to be powered on. The vacuum hose also needs to be connected to the vacuum chuck, but should not be turned on initially The machine axes will then need to be moved up and out of the way in order easily mount the silicon substrate onto the vacuum chuck. The silicon substrate containing the CNT dominos should now be placed on the vacuum chuck and aligned parallel to the major axis of the roller and against the small lip on the vacuum chuck. The wire gauge chucks should be inserted into the larger chucks and locked down. Then, the desired roller should be inserted into the wire gauge chucks and secured. Finally, the vacuum pump should be turned on, in order to secure the silicon substrate.

5.8.2 Toppling/Flattening

The first step that needs to be completed is the placement of the silicon substrate into the proper position. The CNT dominos need to be aligned with the roller. This will be done by using the overhead camera to view the line of CNT dominos and align it with the roller. The roller should then be lowered down onto the surface of the silicon substrate and the force at this time should be noted. Next, the speed of the roller motor and the rate of translation of the x- axis slide should be set in LabVIEW. Next we will hit start on LabVIEW and run the roller over the CNTs. Once this is done we will move the Z axis slide back up over the toppled CNTs and move the flat surface over the top of all the CNTs.

Next, we will manually drive the Z axis slide down so that the flat surface has contacted and begun to condense the toppled CNTs. At this time the force readout from the sensor should be noted and using this, the proper force should then be applied in order to provide enough force to densify the CNTs by 50 times. The Z axis will then be lifted up while making sure that none of the CNT dominos have accidently stuck to the bottom surface.

5.8.3 Printing Process

Finally the printing process is completed. The toppler roller is swapped out, along with the micro chucks that holds it in place. In its place a larger printing roller made of PDMS must be inserted and secured. This roller setup is moved in the Z direction downwards until the roller is contacting the silicon substrate. At this time the proper speeds of the roller motor and the x-axis slide is specified in LabVIEW. Then we again hit start on our LabVIEW program to set the roller and slide in motion. This motion picks up the CNTs onto the roller. Next, we swap out the original empty silicon substrate for another secondary substrate if necessary. Calibrate…. The proper speeds for the two motors are again specified in LabVIEW. The roller is started and will roll over the secondary substrate in order to print the processed CNTs.

5.8.4 Electronics

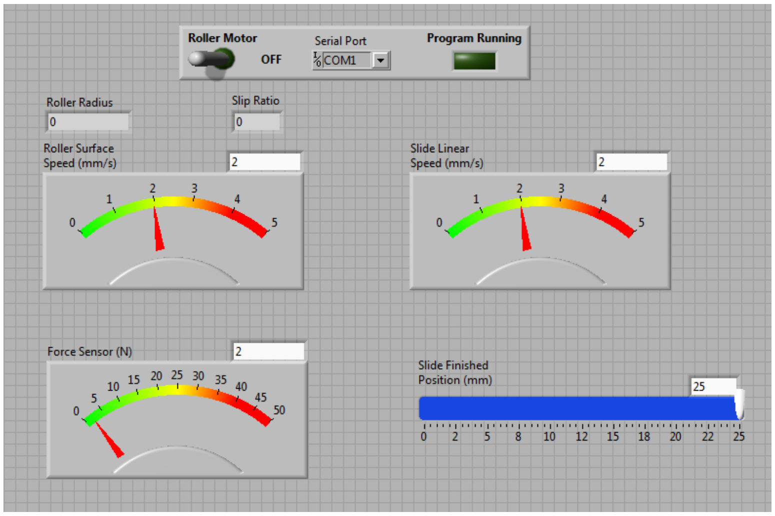
Both absolute positions and speeds of the rolling and sliding motors are controlled by LabVIEW. Another input parameter in the vi file is the roller radius, from which LabVIEW is able to compute the slip ratio, which is the ratio of the linear speed of the slide and the surface speed of the roller. In other words, slipping would occur when the slip ratio is not 1; therefore, user could be immediately informed the slipping situation. We can also collect data from the force sensor, which measures the force acting on the roller, through data acquisition card and LabVIEW interface. Figure 29, p. 35 shows the front panel of the LabVIEW vi file that we use in this application.

Also, the alignment camera would be connected to the computer, recording the current processing procedure, so that the processes could be viewed simultaneously and it could keep a record for future reference.

5.8.4.1 How to use the LabVIEW file

First, both rolling and sliding motors should be connected to the controllers, which should be connected to the computer by a USB cord. Then, 12 volts voltages should be supplied to both controllers. Green lights would be emitted on the controllers, indicating they are supplied with power. Next, users should open the LabVIEW vi file, and click the roller motor switch to “on.” If all parts are well-connected and power supplies are stable, the motors would start rotating when the speeds and the absolute positions are adjusted. For force measurement, a -5 volts voltage needs to be supplied to the force sensor, and the output voltage should be connected to the data acquisition card (pin 2 for the ground and pin 3 for the output voltage), which is connected to the computer as well. Once a force is acting on the force sensor, the value of the force sensor section on the front panel would be changed accordingly.

Figure 29. Front Panel of LabVIEW VI File



5.9 Validation

It is necessary to experimentally validate the final prototype after its assembly to determine that it is able to meet the customer requirements. We identified the customer requirements that are most important that we feel are essential to validate. These customer requirements that are required to be validated include:

- Flatten and condense at least 50x
- Achieve uniform densification within +/- 10%
- Transfer the flattened and condensed CNTs with a 10 μm position tolerance

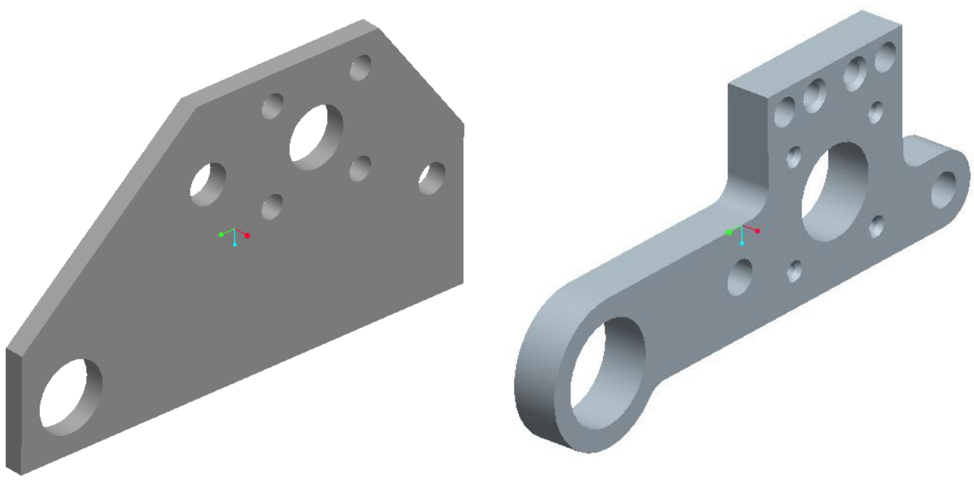
Testing of a number of CNT domino substrates is required in order to get a precise concept of how well we can meet these requirements. The densification test can be completed by optically scanning the surface of flattened CNT dominos in order to determine their final height, and thus our final density based on the original dimensions of the CNT dominos. This method can also be able to tell us if we are within the +/- 10% final value in density. The positioning can be determined by SEM and a stereo microscope that we will set up above the transferred CNTs. This will be a good enough zoom to tell if we are within the 10 μm for final position that we are trying to achieve. With enough testing of our machine we should be able to know exactly what we need to make changes to and how we will make these changes to meet the customer requirements.

6 ENGINEERING CHANGES

In the time between Design Review 3 and the completion of our machine, a few engineering design changes became necessary. They fell into two categories: part refinement and necessary assembly changes.

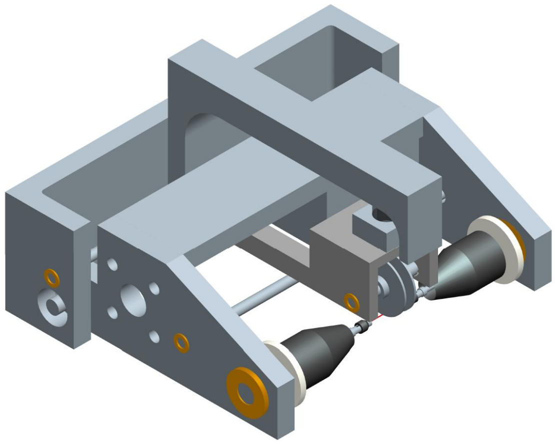
Many parts were refined when revisited for creating their engineering drawings. Nearly all parts were revised with regard to mounting hardware, such as moving to 82° chamfers for all connections, and sizing locating pins. However, some parts were refined also for easier machining, or more efficient use of material. One example of this is part# 4.3.1, the roller sideplates, shown below in Figure 30. This part was originally to be cut from ¼" aluminum, and drilled for driveshaft, roller, and motor mount holes. In order to increase the precision of the part, the thickness was increased to ½". Secondly, the location of the shafts were optimized for rolling quality by locating them in vertical plane with each other, and the location of the driveshaft was optimized for final head design packaging. When the waterjet then became available to fabricate the part, we had much more freedom in the part shape, and this freedom was used to save on necessary raw material and part weight, which will help the resolution of compressive force we can measure at very low loads.

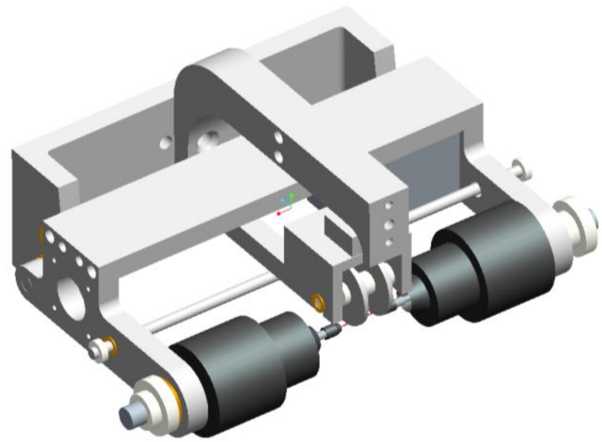
Figure 30. Alpha and Final Roller Sideplate Design



As our parts arrived and we began fabrication, other engineering changes became necessary. The largest change was necessitated by the large drill chucks, which were larger than anticipated. They did not fit inside the roller sideplates (Appendix D, component 4.3.1), which were constrained by the support wings (component 4.1.1). Instead of purchasing a larger piece of aluminum for the support wings, which would then later require even more material removal, we changed the design to accommodate the sideplates outside of the support wings. This change also allowed for simpler assembly. See Figure 31, p.37 for an illustration of the alpha and final head designs.

Figure 31. Alpha and Final Head Designs





These examples are only of our many design changes. Please see Appendix J, p. 66 for a complete list.

7 DISCUSSION

7.1 Strengths and Weaknesses

The major strength of our design is that it will allow for much more precise rolling of the CNTs as compared to the existing state of the art design. Our design has a camera that can be used check the alignment of the roller/toppler to the CNTs themselves. This alignment can then be adjusted using the turntable mounted underneath the vacuum chuck. The turntable has a very fine resolution (0.1 degrees) to aid in the adjustment. We are also much more precise with our applied force. We can now maintain a much more uniform force across the top of the CNTs because of the spring and force sensor setup on the top boom. The force sensor allows us to monitor the force in real time and coupled with the LabVIEW program, will allow us to record the force applied during operation. Our design is also much better at maintaining alignment of the roller during operation. The roller is constrained along the roller axis and will be sure to maintain a straight attack angle of the CNTs. Furthermore, the roller will not deflect while in operation. Our design implements two idlers that are constrained on an axis above and behind the roller axis. These idlers contact the top of the roller and apply a force radially to prevent the roller from bending while it is in operation.

The major weakness of our design is that it is somewhat difficult to operate. Each of the stages (toppling, flattening, and printing), require some sort of setup. This will slow down the entire process and make it difficult to process multiple CNT substrates in a short amount of time. Another weakness of our design is that it is not as portable as we had originally intended it to be. The large amount of thick aluminum parts used in fabrication makes it very difficult for 1 person to safely move the prototype. Finally, some of press fit axles in our design are not aligned quite as well as originally intended. This will result in some misalignment in the roller subassembly, which will hurt our precision of operation.

7.2 Improvements

A possible improvement we could make to make the prototype easier to use would be to move the flattening face on the underside of the follower arm. This would allow us to flatten the CNTs without the need to add the two flattener halves. In this case the force sensor and spring configuration would also have to be moved underneath the vacuum chuck in order to get an accurate reading. The portability, or weight, of the prototype could be reduced quite a bit by changing the material of the base plate from 6061 aluminum to a polymer like a glass reinforce PA material. This would reduce the weight of this large bulky part by more than half. The assembly of the press fits could be improved by being more careful to align the axles while they are press fit. This will allow us to more accurately assemble the prototype and thereby increase the precision of operation of the prototype.

8 RECOMMENDATIONS

After researching, manufacturing our prototype, we have several recommendations for future work in this area.

- To ensure a more uniform densifying result, we recommend re-manufacture the idlers because the surface finish of the current idler is not perfect, which may cause some bumping during the rolling process. The dimension of the idler is provided in Appendix F, p. 55. Also, consider choosing steel for this part, as steel is harder and will resist denting more effectively at high compressive loads.

- To obtain a better visual of the densifying process, we recommend buying an additional camera, so that both vertical and horizontal view could be captured and no substantial twisting is required for the camera support pipe. For the mounting position, we recommend the other camera to be mounted on the other side of the instrument, so that both cameras have enough room to be positioned and capture images from different angles.

- We would also recommend making the LabVIEW vi file more user-friendly by limiting the numbers of buttons that are required to push in order to run the system. More motor control functions are also recommended, for example: motor acceleration control and motor torque control.

- In order to have the most optimal densifying result, we recommend users of the instrument monitor that both rolling chucks are perfectly level, so the roller would also be level, providing very uniform and most desirable results.

9 CONCLUSION

The purpose of this project is to physically process carbon nanotubes (CNTs) grown vertically in a chemical vapor deposition process (CVD) to a horizontal and densified condition, and to transfer these CNTs to another substrate. This has been accomplished with the construction on a laboratory CNT domino toppler, which functions to topple, condense, and transfer CNTs through rolling, or toppling and flattening, and then rolling with a PDMS roller. Our design process including customer requirements, QFD generation, design concepts, and concept selection are shown in Sections 3-4. The final design is explained in Section 5, p. 17. The design required the design and fabrication of many custom parts, engineering drawings of which are shown in Appendix F, p. 52.

The machine design, fabrication, and assembly are complete, and motor control is functional. The machine is ready for laboratory use in the processing of CNT dominos. Unfortunately, we have been unable to validate its function through rolling and toppling tests. Also, the LabVIEW control software does not integrate all desired functionality at this time. Further work may be done based on our recommendations in Section 8.

We hope our CNT toppler is useful in Professor Hart's nanofabrication laboratory, and its improved functionality allows much more varied and repeatable CNT processing experiments. We are confident the machine meets all customer requirements, and its modular design allows modification and expansion for unseen future needs.

10 ACKNOWLEDGEMENTS

We would like to thank our sponsors Professor John Hart and Sameh Tawfick for their support throughout this project. Professor Hart was also our section instructor, and guided us in the details outside of machine design. Sameh Tawfick was an invaluable resource in both CNT experience, and worked with us by fabricating CNT domino substrates, our PDMS roller, and help with LabVIEW and our stepper motors. We would also like to thank Tracie Straub for her help and enthusiasm in purchasing our many parts, and Professor Albert Shih for organizing the project opportunities and scheduling an informative lecture series. Finally, we need to thank the Wilson Student Team Project Center staff and facilities, without which machine fabrication would have been impossible.

11 REFERENCES

[1] Professor John Hart, personal communication

[2] Sameh Tawfick, personal communication

[3] Meitl, M., Zhu, Z., Kumar, V., Lee, K., Feng, Huang, Y., Adesida, I., Nuzzo, R., and J. Rogers, "Transfer Printing by kinetic control of adhesion to an elastomeric stamp", Nature Publishing Group Vol. 5, 11 Dec. 2005, **33-38** (2006)

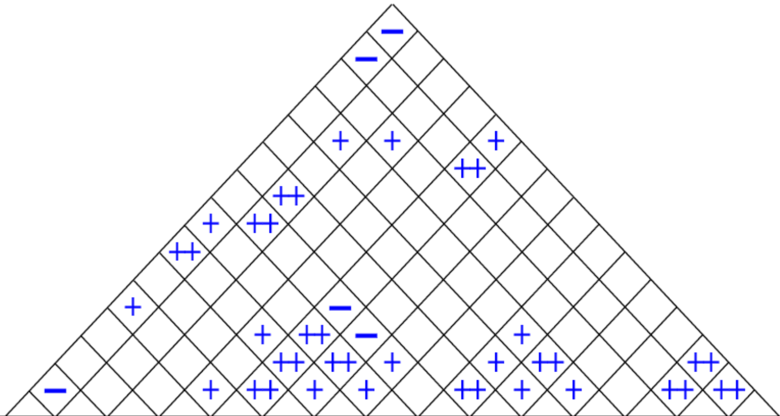
[4] Ahmed, S.l.-U., Bregliozzi, G., and H. Haefke, "Microtribology of Silicon Oxide and Carbide Surfaces", Wiley Interscience, Tribotest 2006, **175-184** (2006)

[5] Zhiping, Y., Zhang, H. P., and M. Marder, " Dynamics of Static Friction Between Steel and Silicon", Center for Nonlinear Dynamics and Department of Physics, University of Texas, Austin, 9 September 2008**, 13264-**13267 (2008)

[6] Velmex Inc. Bislide Product Specifications. http://www.Velmex.com

APPENDIX A – MODIFIED QFD

Figure A1. Modified QFD



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	x	x	▲	▲	▲	▲	x	x	x	▲	▲	x	x
					Simple and robust design	Allows multiple flattening, transferring contact points	Include stereo microscope setup	Sufficient absolute compressive force	Compressive force uniformity	Tight construction tolerances	Heavy, machined parts	Precision silicon chip mounting	Quick and simple silicon chip mounting	Allow Process changes and additions	Control component voltages	Compatible with many secondary substrates	Use precise sensors to monitor operation	Automatic, precision operation	Interface with Controlling Computer
1	9	10.9	10.0	Produce Horizontal CNTs		▲		▲	▲	⊙		○			▲			▲	
2	9	10.9	10.0	Maintain precise CNT alignment	▲					⊙	○	⊙						○	
3	9	10.9	10.0	Condense nanotubes by 50x (densify)		▲		⊙	⊙									▲	
4	9	10.9	10.0	Achieve uniform densification	▲			▲	⊙	⊙	○	⊙					⊙	⊙	○
5	9	10.9	10.0	Allow careful viewing of entire process			⊙												
6	9	10.9	10.0	Is a repeatable and stable process	⊙					⊙	○	⊙	▲				○	⊙	⊙
7	9	10.9	10.0	Transfer aligned CNTs to other media		⊙									○	○			
8	9	10.9	10.0	Provide a means to tune densification		▲								○			⊙	⊙	⊙
9	9	2.2	2.0	Easy to use	○		○					○	⊙				○	⊙	▲
10	9	10.9	10.0	Durable	⊙					⊙	⊙	○							
				Target or Limit Value	5 year lifespan		Use stereo microscope available in lab		As necessary to maintain 10% densification variation	.001 in									
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	4	5	2	2	7	7	2	5	4	7	7	6	10	10	10
				Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	3	3	3	9	9	9
				Weight / Importance	223.9	130.4	104.3	119.6	206.5	489.1	195.7	365.2	30.4	32.6	43.5	32.6	234.8	367.4	230.4
				Relative Weight	8.0	4.6	3.7	4.3	7.4	17.4	7.0	13.0	1.1	1.2	1.5	1.2	8.4	13.1	8.2

APPENDIX B – OTHER CONCEPT ILLUSTRATIONS

Figure B1. Break Catalyst and Topple

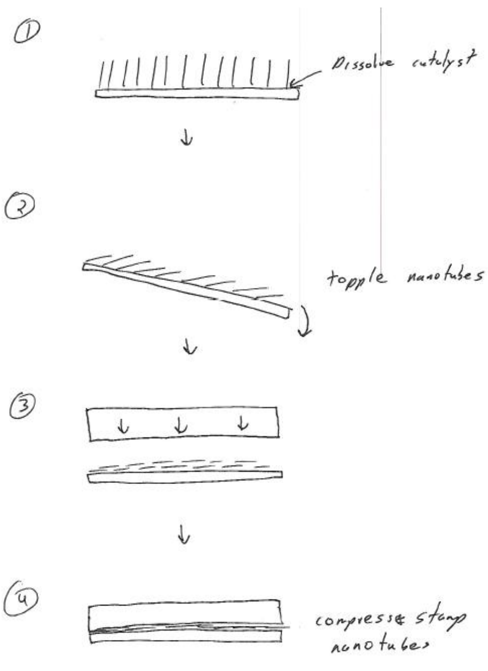


Figure B2. Magnet

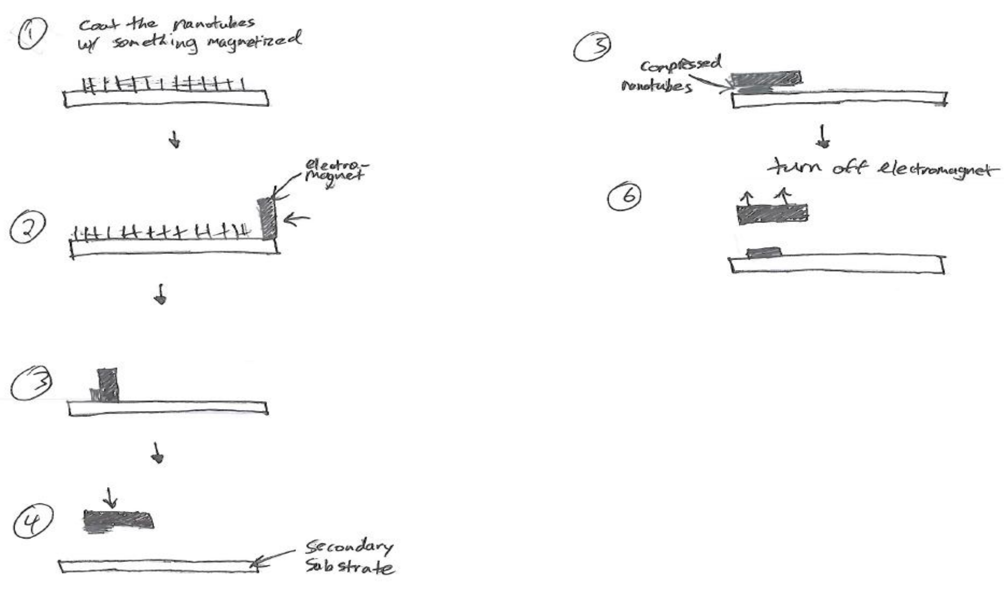


Figure B3. Tweezer

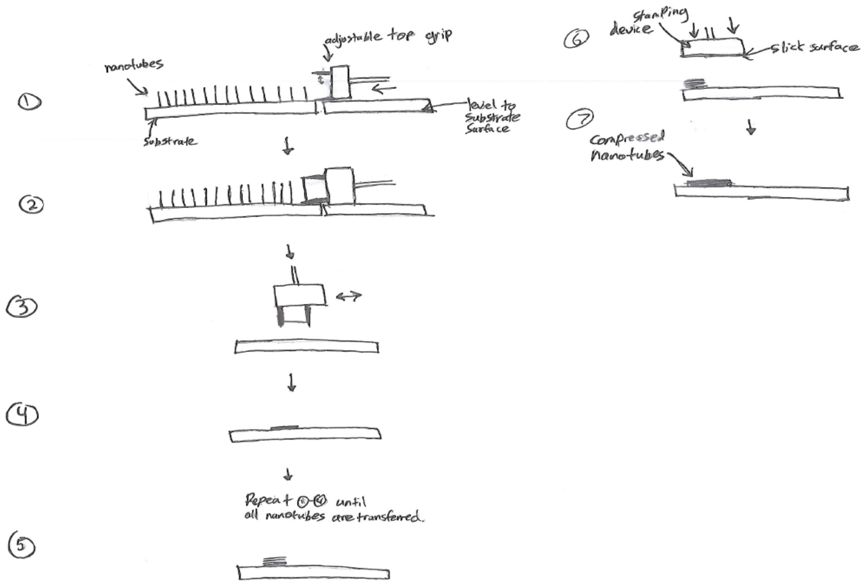


Figure B4. Hinge

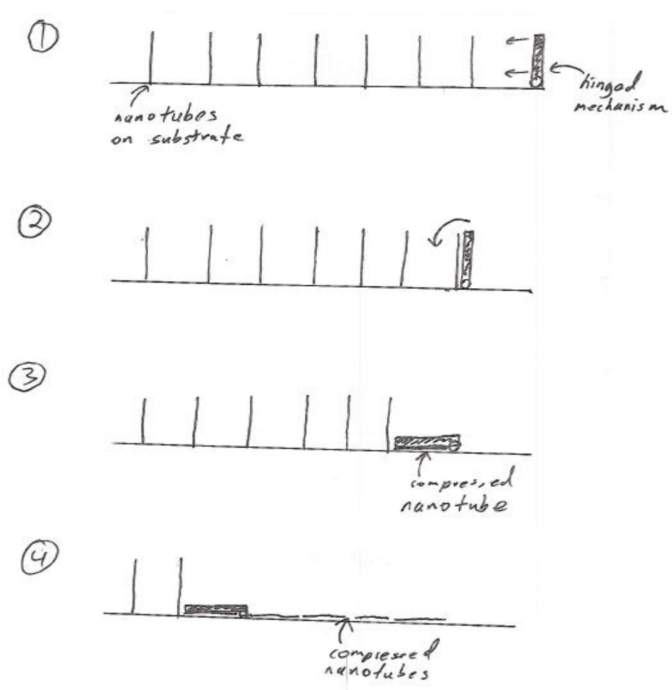
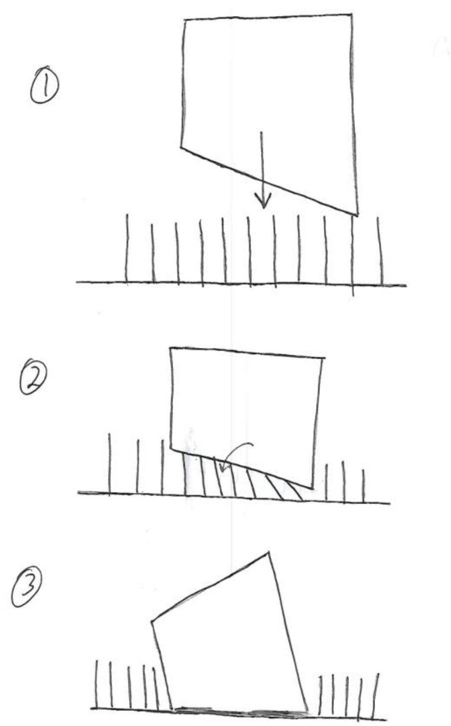


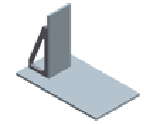
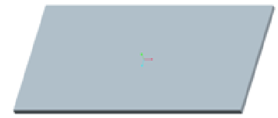
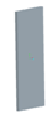
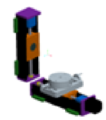
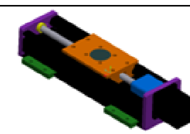
Figure B5. Wedge Crusher

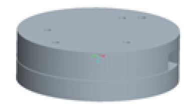
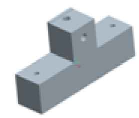
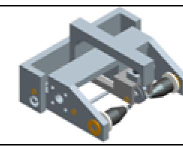
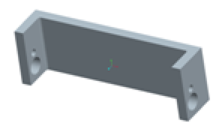
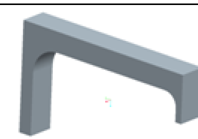
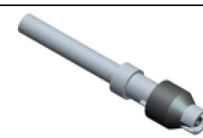


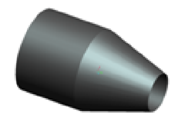
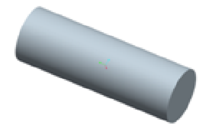
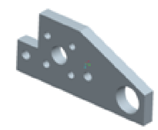
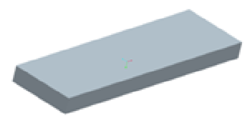
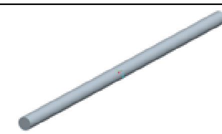
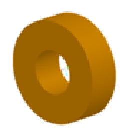
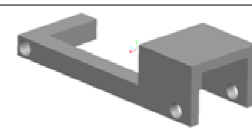
APPENDIX C – SAFETY ANALYSIS

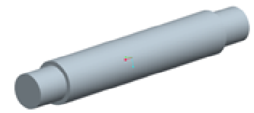
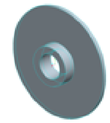
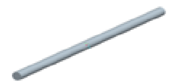
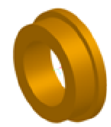
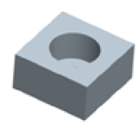
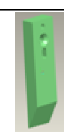
Item Id	user	part/task	Hazard Category	Hazard	Cause/Failure Mode	Severity	Exposure	Probability	Risk	Reduce Risk	Severity	Exposure	Probability	Risk	Person	Status
1.1	All Users	Primary silicon substrate	mechanical	crushing	Applying too much force downwards onto the silicon substrate	Minimal	Remote	Unlikely	Low	Attach a warning label stating a maximum reccommended load for a silicon substrate	Minimal	None	Negligible	Low	All Users	Complete
1.2	All Users	Both Bi-slides	mechanical	pinch point	The Bi-slides are not completely covered and could be accessed with a hand or finger	Serious	Occasional	Unlikely	Moderate	Attach a warning label to the bislides	Serious	Remote	Negligible	Low	All Users	TBD
1.3	All Users	Z-axis Bi-slide	mechanical	break up during operation	applying too much force to the vertical Bi-slide during crushing beyond what it can handle	Minimal	Occasional	Possible	Moderate	Add a label stating a maximum force that the slide can be driven at	Minimal	Remote	Unlikely	Low	All Users	On-going
1.4	All Users	All motors and control systems	electrical / electronic	improper wiring	Improperly wired motors and controllers connected to the drivers and computer	Minimal	Occasional	Possible	Moderate	Double check the wiring of the electrical system and optical setup before use	Slight	Remote	Unlikely	Low	All Users	TBD
1.5	All Users	roller stepper motor	electrical / electronic	overloading	Driving the roller motor at too high of a torque	Minimal	Occasional	Possible	Moderate	Limit the rate at which the motor can driven in Labview	Minimal	None	Negligible	Low	All Users	TBD
1.6	All Users	Labview setup	electrical / electronic	unexpected start up / motion	Unexpected start of the machine from accidental Labview activation, or the machine moving outside of its possible range	Slight	Remote	Unlikely	Low	Train the users how to use the Labview and restrict the motion on the program to accepable values	Minimal	Occasional	Unlikely	Low	All Users	On-going
1.7	All Users	Labview setup	electrical / electronic	software errors	Labview software set up improperly	Minimal	None	Possible	Low	Test the program before running actually processing any CNTs	Minimal	Remote	Unlikely	Low	All Users	TBD
1.8	All Users	General operation	ergonomics / human factors	human errors / behaviors	Machine operated by someone who doesn't know how to operate it properly	Slight	Occasional	Possible	Moderate	Make sure that only our group and sponsors are the ones operating the machine	Slight	None	Negligible	Low	All Users	On-going
1.9	All Users	Base subsystem	noise / vibration	fatigue / material strength	The base, including the vacuum chuck, turntable, and base slides) fatigues over time when subjected to the compression force of the machine	Minimal	Remote	Unlikely	Low	Use high strength steels and aluminum alloys for the base subsystem	Minimal	None	Negligible	Low	All Users	Complete
1.9	All Users	Room conditions	ingress / egress	inadequate lighting	the room isn't properly lit	Minimal	Remote	Possible	Low	Be sure to use the machine in a well lit area. This makes it difficult to align the roller to the CNTs	Minimal	None	Negligible	Low	All Users	Complete
1.10	All Users	Primary silicon substrate	ventilation	air contaminents	Breathing in the CNT microparticles is a potential hazard	Minimal	Remote	Possible	Low	keep the CNT substrates away from face when possible	Slight	Remote	Negligible	Low	All Users	On-going
1.11	All Users	Primary silicon substrate	chemical	chemical / toxicity effects felt at distant time / place	CNTs can get stuck in the skin if they aren't handled carefully	Serious	Occasional	Possible	High	Wear gloves while handling the CNT substrates	Slight	Remote	Unlikely	Low	All Users	On-going
1.12	All Users	vacuum chuck or vacuum hose	fluid / pressure	vacuum	the vacuum isn't secured well enough to the vacuum chuck	Minimal	Occasional	Unlikely	Low	Make sure the user is trained to tighten the vacuum hose into the vacuum chuck before	Minimal	Remote	Unlikely	Low	All Users	On-going

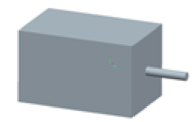
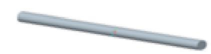
APPENDIX D – COMPONENT LIST

Component ID	Component Name	Description	Function	Fabrication	Assembly	Picture	Step 1	Step 2	Step 3
1	**Chassis**	Provide rigid relationships between all components							
1.1	Base Plate	1/2" 6061 Plate	Provide square and solid mounting points for the assembly	Milled	Will include precise holes for locating pins		Drill centers for all holes	Drill to correct diameters for threads	tap holes
1.2	BiSlide Support Plate	1/2" 6061 Plate	Provide square and solid mounting points for the vertical BiSlide	Milled	Will include precise holes for locating pins, including slots for Thorlabs VB01		Drill centers for all holes	Drill to correct diameters for threads	tap holes
1.3	Thorlabs VB01	Purchased, Aluminum	Hold BiSlide Support Plate	Purchased	Drilled for locating holes, tapped 1/4-20				
2	**Constrained Axes**	Allow precise adjustment and drive of required degrees of freedom							
2.1.1	Velmex BiSlide	Motor driven linear stage	Constrain and drive X axis motion	Purchased	Attached to base plate with Velmex cleats				
2.1.2	Velmex BiSlide	Hand driven linear stage	Constrain Z axis motion	Purchased	Attached to base plate with Velmex cleats				
2.1.1/2.1	Velmex BiSlide Cleats	Attach bolt locations to extruded aluminum BiSlide	Fixture BiSlides	Purchased	Attach with machine screws				

2.1.3	Velmex A40 Stage	Hand driven linear stage	Constrains Y axis adjustment	Purchased	Attach to BiSlide with supplied Velmex adapter plate				
2.1.4	Velmex 4" Turntable	Hand-adjusted rotary stage	Allow Z axis rotational adjustment	Purchased	Attached to A40 with supplied Velmex adapter plate				
3	**Original substrate mount**	Monolithic machined 6061 Al	Provide stable mount for incoming silicon substrate	Machine from 1" 6061	Attach to turntable with machine screws		Mill shape from 1" 6061	mill holes	Vacuum hole drill and proper threading
4	**Head**	Contain mechanisms which allow processing of CNT dominos							
4.1.1	Support Wings	Monolithic machined 6061 Al	Provide stable and square mount for rear pivot axles	Water jet cut, then machine from 2" 6061	Attaches to custom Velmex adapter with 1/4-20 machine screws and two positioning pins		premachine	Waterjet+finish mill	
4.1.2	Support Boom	Monolithic machined 6061 Al	Provide solid and square application of downward force to spring and follower	Water jet cut, then machine from 1" 6061	Attaches to custom Velmex adapter with 3/8-16 machine screws and two positioning pins		premachine	Waterjet+finish mill	needs bigger counterbore
4.2.1	Roller Pin	Varies	Topple and flatten CNT dominos	Purchased	Chucked in wire gauge chucks				
4.2.2	Wire Gauge Chuck	Micro Chuck	Hold small diameter rollers	Purchased	Chucked in precision chucks				

4.2.3	Precision Chuck	Macro Chuck	Hold wire gauge chuck, or larger diameter rollers	Purchased	Attached to 33J taper shaft					
4.2.4	1/2" to 33J Taper	Adapter for fitting Precision Chuck to machine	Provides 1/2" round surface for precision chuck	Purchased, modified on lathe	Press fit in a pair of R8 bearings		lathe			
4.2.5	R8 Bearing	Standard ABEC1 bearing	Allow roller assemble to rotate in roller side plates	Purchased	Press fit in roller side plates					
4.3.1	Roller Side Plate	1/2" 6061	Provide mounting for stepper moter and transmission, hold roller assembly	Water jet, then final milling	Press fit bearings on both ends assure accurate locating		Waterjet shape	mill holes	split and finish	
4.3.2	Roller Side Plate Stabilizer	1/2" 6061	Stabilize the two roller side plates in order to assure roller position	Water jet, then final milling	Milled contact surfaces assure sideplate parallelism, locating pins assure roller remains in plane		mill	plane sides	2 position holes	2 threaded holes
4.3.3	Roller Axle	3/8" stainless steel	provide solid pivot axis for roller side plates and roller assembly	Lathe	Lathed to allow press fit between roller side plate allows external and aligned assembly of roller sideplates		lathe	lathe to length		
4.3.4	R6 Bearing	Standard ABEC1 bearing	Allow roller axle to rotate in support wings	Purchased	Press fit in support wings					
4.4.1	Follower Arm	Monolithic machined 6061 Al	Provide radius for idlers while maintaining alignment	Machined from 2" 6061	Press fit bearings on both ends assure accurate locating		mill	redesign		

4.4.2	Idler Shaft	1/2" Threaded stainless steel	Provide axis for idlers, allow lateral idler adjustment	Lathed	press fit in bearings		lathe	cut down to 3/8 in.? smooth		
4.4.3	Idler	6061 Al	Applies force to roller to flatten CNTs	Lathed	Aligned and tapped through hole assures true rolling		lathe + mill	lathe profile	drill center hole on lathe	drill setscrew hole on mill
4.4.4	Follower Shaft	1/4" stainless steel	Provides solid pivot support for follower	Lathed	press fit in bearings		lathe	c clip grooves	correct length	
4.4.5	Bearing	Flanged and double shielded	Used throughout head for follower pivots and drivetrain	Purchased	Press fit					
4.5.1	Force Sensor	Measures normal force	In series with spring and follower to measure force applied at roller	Purchased	adhered in series between follower and spring perce, alignment not critical					
4.5.2	Spring	Provides reasonable spring constant	Helps increase pressure resolution adjusted from displacement, reduces change in force applied over surface imperfections	Purchased	Placed in spring perch, alignment not critical					
4.5.3	Spring Perch	1/2" 6061	Constrains spring	Milled	adhered to force sensor		milled			
4.6.1	Toppler Attachment	1/2" 6062	Attaches to boom to topple CNT dominos	Milled	Slot and machine screws		milled	cut angle		

4.6.2	Flattener	1" 6062	Attaches to roller followers to flatten CNTs	Milled	2 halves assembled		milled		
4.7.1	Stepper Motor	NEMA 17 standard sized	provides drive and control of roller rotation	Purchased	Face mounts to roller sideplates, alignement not critical				
4.7.2	First Reduction	Timing belt and pulley pair	Transmits torque, allows the motor to run at a higher speed to reduce acclerations inherent in advancing from step to step	Purchased, modified on lathe	Setscrews engage flats in motor shaft and torque shaft				
4.7.3	Torque Shaft	1/4" stainless steel	Transmits torque to both sides of the machine to reduce stress on roller	Lathe	Press fit to bearings		lathe	length	
4.7.4	Second Reduction	Timing belt and pulley pair	Transmits torque, allows the motor to run at a higher speed to reduce acclerations inherent in advancing from step to step	Purchased, modified on lathe	Setscrews engage flats in torque shaft and 1/2" to 33J taper		milled	enlarge hole to 1/2 in	
4.8.1	Adapter Plate	1/2" 6062	Allows boom and wings to attach to Z axis BiSlide	Milled	Locating pins and machine screws (3/8-16)		Mill		

APPENDIX E – BILL OF MATERIALS

Vendor + contact	Part#	Item name	Function or module	Qty	Unit (each, box, etc.)	Unit price	TOTAL
Velmex, (800) 642-6446	MC-2	bi-slide cleats, 1.42" c-c	attach bislides to fixtures	8	each	5	40
Velmex, (800) 642-6446	MSPP-2	adapter plate, bislide-a40	attach parts to bislides	1	each	52	52
Velmex, (800) 642-6446	MN10-0050-E01-21	Motor-driveable bi-slide	y axis	1	each	744	744
Velmex, (800) 642-6446	MN10-0050-E01-11	Manual bi-slide	z axis	1	each	748	748
Velmex, (800) 642-6446	A4006W1-S4-TL	A40 2" slide, thumbscrew-on-leadscrew lock	x axis	1	each	342	342
Velmex, (800) 642-6446	A4007TS	4"dia rotary table	rotary	1	each	348	348
Velmex, (800) 642-6446	MB-1	BiSlide cleat bolts, 10pk	attach cleats to fixtures	2	10pk	3	6
Portescap (610) 235-5499	23H118D30B	NEMA 23 One Stack Hybrid Step Motor	Drive the bislide	1	each	87.9	87.9
All Motion (510) 471-4000	EZHR23	http://allmotion.com/EZHR23description.htm	Control NEMA 23 X-axis motor	1	each		
All Motion (510) 471-4000	USB485	USB to 485 Converter	Connects PC USB port with NEMA 23 Controller	1	each	49	49
Likenewpcs (303) 293-8100	USB A/B 2.0 6ft	AR 6' A/B USB 2.0 Device Cable (Black)	A cable to connect the USB485 converter to PC	1	each	4.99	4.99
Thorlabs, http://www.thorlabs.com	VB-01	vertical bracket for breadboards	support z-axis	2	each	83.6	167.2
McMaster, mcmaster.com	MM8472A11	1/4, 3/16 locating pin	Aid in assembly alignment	10	each	2.02	20.2
McMaster, mcmaster.com	MM8472A12	5/16, 1/4 locating pin	Aid in assembly alignment	14	each	2.02	28.28
McMaster, mcmaster.com	MM8472A19	1/4, 3/16 diamond locating pin	Aid in assembly alignment	10	each	3.27	32.7
McMaster, mcmaster.com	MM8472A21	5/16, 1/4 diamond locating pin	Aid in assembly alignment	6	each	3.33	19.98
McMaster, mcmaster.com	MM95412A752	1/2-20 2" threaded SS rod	Follower shaft	2	Pack of 1	2.88	5.76
McMaster, mcmaster.com	90128A947	10-32 1" machine screws	vacuum chuck to turntable	1	pack of 25	6.13	6.13
McMaster, mcmaster.com	MM90257A029	1/2-20 SS nut, 7/16wrench	follower shaft	1	Pack of 25	6.81	6.81
McMaster, mcmaster.com	MM93085A540	1/4-20 SS machine screw, 100deg head, .75" length	Assembly	1	Pack of 25	11.1	11.1
McMaster, mcmaster.com	MM93085A542	1/4-20 SS machine screw, 100deg head, 1" length	Assembly	1	Pack of 10	5.22	5.22
McMaster, mcmaster.com	91771A628	3/8"-16 SS machine screw, 82" head, 1.5" length	assembly	1	pack of 10	9.98	
McMaster, mcmaster.com	92185A542	1/4-20 SS allen head screw, 1"	Assembly	1	Pack of 10	6.33	6.33
Enco, www.use-enco.com	290-1020	Keyed precision chuck, 1-13mm capacity, 33JTaper	Roller assy	2	each	29	58
McMaster, mcmaster.com	30505A5	Wire gauge micro chuck	roller assy	2	each	6.47	12.94
McMaster, mcmaster.com	2811A59	1/2" straight shank to jacobs taper arbor	roller assy	2	each	14	28
McMaster, mcmaster.com	60355K36	1/2"ID, 1.125" OD bearing	for chucks	4	each	6.61	26.44
McMaster, mcmaster.com	57155K322	1/4"ID, .375" OD flanged cartridge ball bearing	many places in roller head	8	each	9.88	79.04
McMaster, mcmaster.com	98555A120	c-clip, 1/4" shaft dia	Assembly	1	100pack	9.14	9.14
McMaster, mcmaster.com	98555A170	c-clip, 1/2" shaft dia	Assembly	1	50 pack	7	7
Alro/ASAP Source, http://www.asapsource.com	SP:SPA6061:01000-6061-12x12	12"x12"x1" 6061 Al plate	Material	1	each	100.73	100.73
Alro/ASAP Source, http://www.asapsource.com	RFA6061:2000-03000-6061-XXX	2"x3" 6061 rectangle section	Material	11	per inch	3.66	40.26
Alro/ASAP Source, http://www.asapsource.com	RFA6061:1500-02000-6061-XXX	1.5"x2" 6061 rectangle section	Material	8	per inch	1.83	14.64
Alro/ASAP Source, http://www.asapsource.com	RD:RDS303:00375-303-036	3/8 SS round	Material	1	36 inches	23.71	23.71
Alro/ASAP Source, http://www.asapsource.com	RDS303:00250-303-036	1/4" SS round	Material	1	36 inches	13.37	13.37
Alro/ASAP Source, http://www.asapsource.com	RDST1018:00500-1018-012	1/2" SS round	printing roller	1	12inches	12.86	12.86
Alro/ASAP Source, http://www.asapsource.com	RDA6061:02250-6061-XXX	2 1/4" 6061 round	Idlers	4	per inch	2.43	9.72
Alro/ASAP Source, http://www.asapsource.com		2"x6"x4" 6061	Material	1	each	37.32	37.32
McMaster, mcmaster.com	1375K16	.58'' (OD) Pulley	Drivetrain	1	each	8.58	8.58
McMaster, mcmaster.com	1375K51	1.21'' (OD) Pulley	Drivetrain	1	each	10.65	10.65
McMaster, mcmaster.com	1375K25	.74'' (OD) Pulley	Drivetrain	2	each	9.28	18.56
McMaster, mcmaster.com	1375K52	1.29'' (OD) Pulley	Drivetrain	2	each	11.02	22.04
McMaster, mcmaster.com	1679K64	Timing Belt between .58'' (OD) Pulley and 1.21'' (OD) Pulley	Drivetrain	1	each	1.21	1.21
McMaster, mcmaster.com	1679K74	Timing Belt between .74'' (OD) Pulley and	Drivetrain	2	each	1.24	2.48
Agent, https://agent.liquiddigital.com.au/	Agent V3 webcam	Agent V3 webcam	Visual	1	each	60	60
McMaster, mcmaster.com	98555A150	3/8" dia c-clips	Assembly	1	pack of 100	9.79	9.79
McMaster, mcmaster.com	60355K35	R6 bearing	Assembly	2	each	5.17	10.34
McMaster, mcmaster.com	MM57155K324	1/4" ID flanged double shielded bearing	Assembly	2	each	7.12	14.24
McMaster, mcmaster.com	90778A016	2-56 1/8" allen head setscrews	Drivetrain	1	pack of 10	8.4	8.4
Lee Spring, leespring.com	LC 058GH 02S	.54"x.625" SS spring, 47.6 lb/in	Compression spring	2	each	5.5	11
Lee Spring, leespring.com	LC 063GH 02S	.54"x.625" SS spring, 65.8 lb/in	Compression spring	2	each	5.72	11.44
Lee Spring, leespring.com	LC 067GH 02S	.54"x.625" SS spring, 85 lb/in	Compression spring	2	each	5.72	11.44
Amazon.com	B00009WBYS	Panavise 817/16 16" CCTV flex mount	Visual	1	each	29.99	29.99
McMaster, mcmaster.com	91771A540	1/4-20 SS machine screw, 82deg head, .75" length	Assembly	1	pack of 50	7.47	7.47
McMaster, mcmaster.com	9432K32	Extension spring, 2.6 lbs/in, 1.562" length	Head Constraint	1	pack of 6	9.53	9.53
McMaster, mcmaster.com	9654K394	Extension spring, 72.25 lbs/in, 1.562" length	Head Constraint	1	pack of 6	11.28	11.28
McMaster, mcmaster.com	91771A546	1/4-20 SS machine screw, 82deg head, 1.5" length	Assembly	1	pack of 25	7.84	7.84
McMaster, mcmaster.com	91847A525	1/2-20 SS machine nut	Assembly	1	pack of 25	9.71	9.71
McMaster, mcmaster.com	8749K11	PVC tube, 9/16 ID	Mold for PDMS	1	per foot	9.3	9.3
McMaster, mcmaster.com	91801A164	M3 SS, 20mm long	For NEMA 17 assembly	1	pack of 50	7.42	7.42
National Instruments	NI USB-6008	Data Acquisition Card	generates data for computer	1	each	169	169
McMaster, mcmaster.com	7887K16	6.4 in" belt neoprene	Drivetrain	2	each	1.81	1.81
McMaster, mcmaster.com	1679K77	6.4" kevlar cord	Drivetrain	2	each	1.24	1.24
McMaster, mcmaster.com	1679K67	5.2" belt	Drivetrain	1	each	1.21	1.21
McMaster, mcmaster.com	9432K42	1.19 lbs-in extension springs, same size as 9432K32	Head Constraint	1	pack of 6	10.55	10.55

APPENDIX F – ENGINEERING DRAWINGS

Figure F1. Base Plate

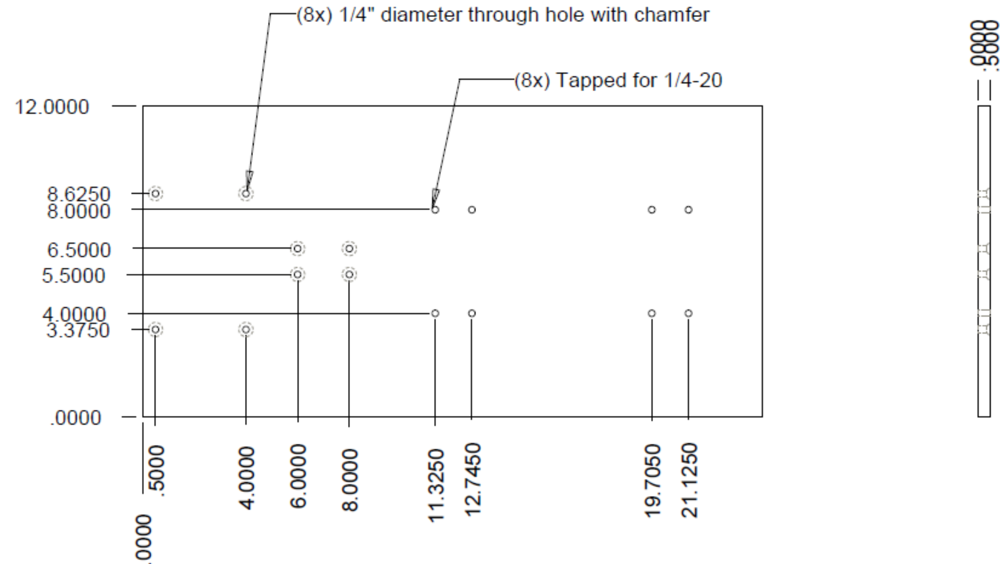


Figure F2. Bislide Support Plate

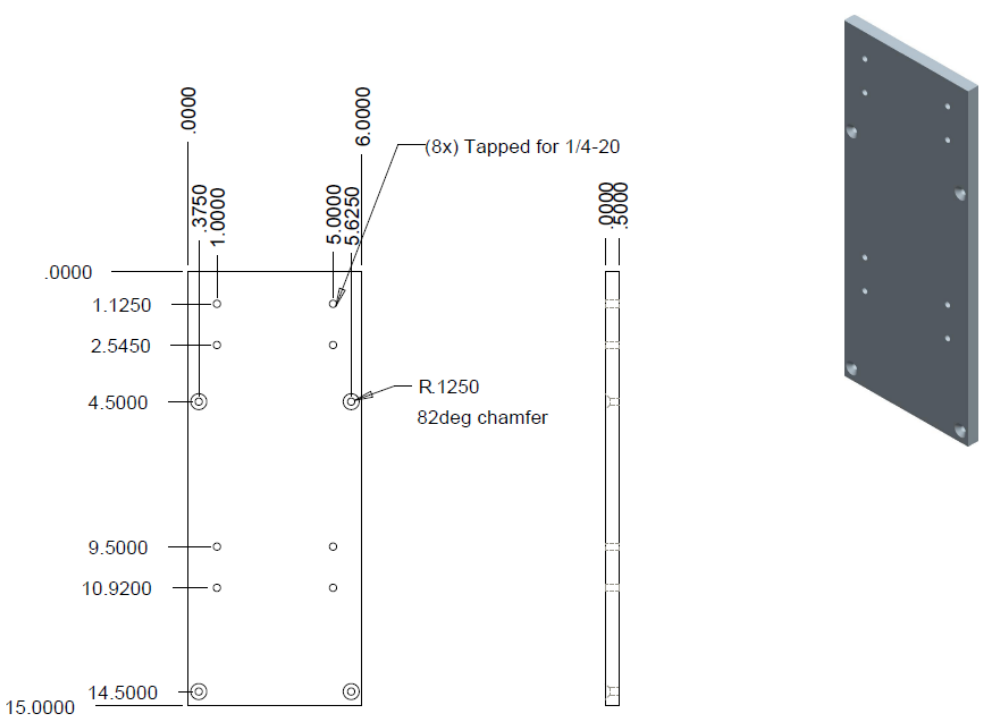


Figure F3. Bislide to Boom Adapter Plate

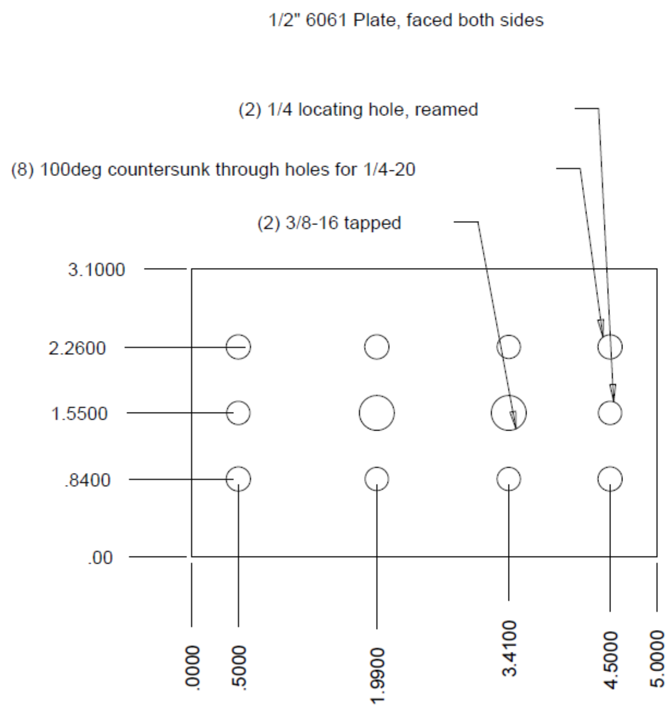


Figure F4. Flattener

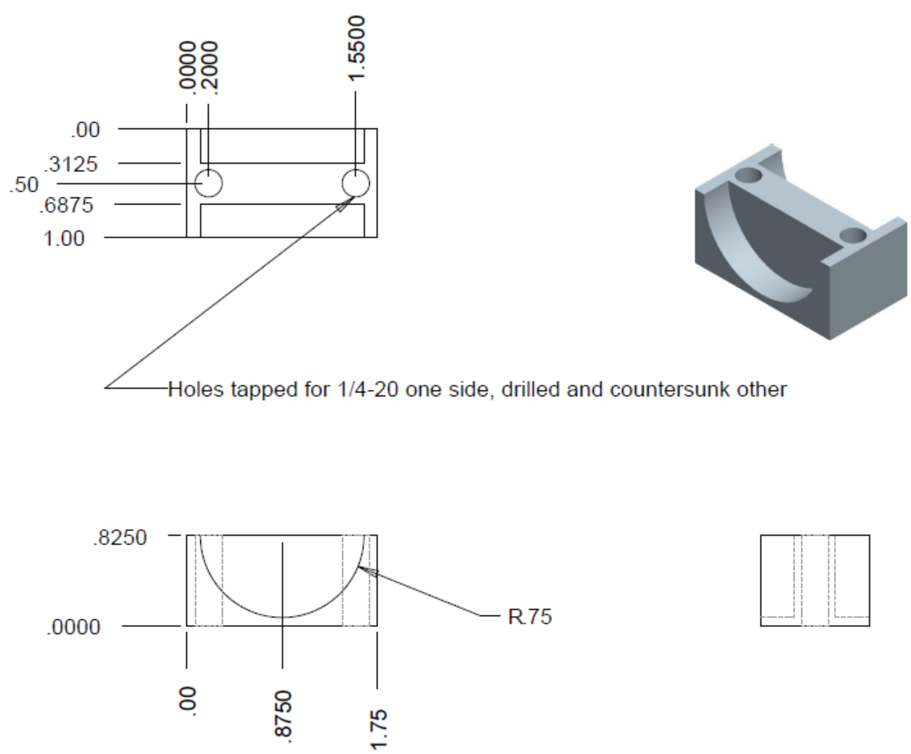
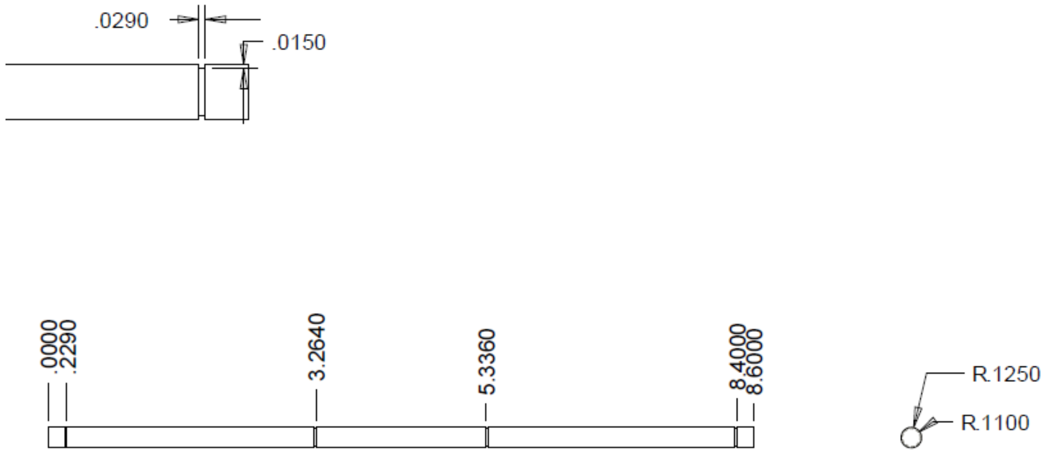


Figure F5. Follower Shaft



Follower Shaft
Note dimensions to edge of c-clip grooves

Figure F6. Follower Axle

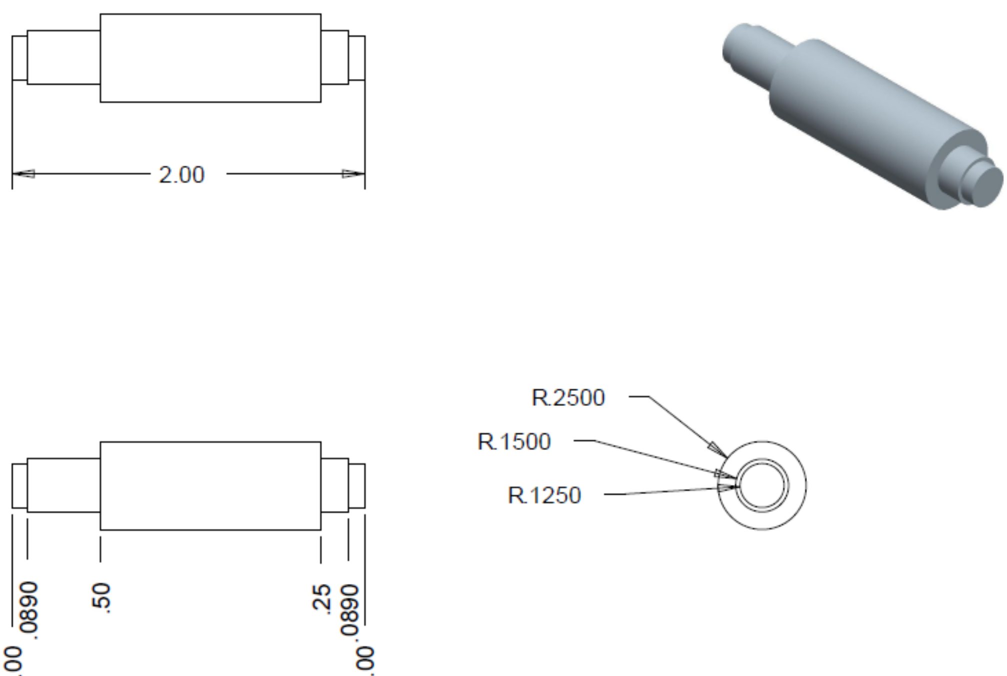
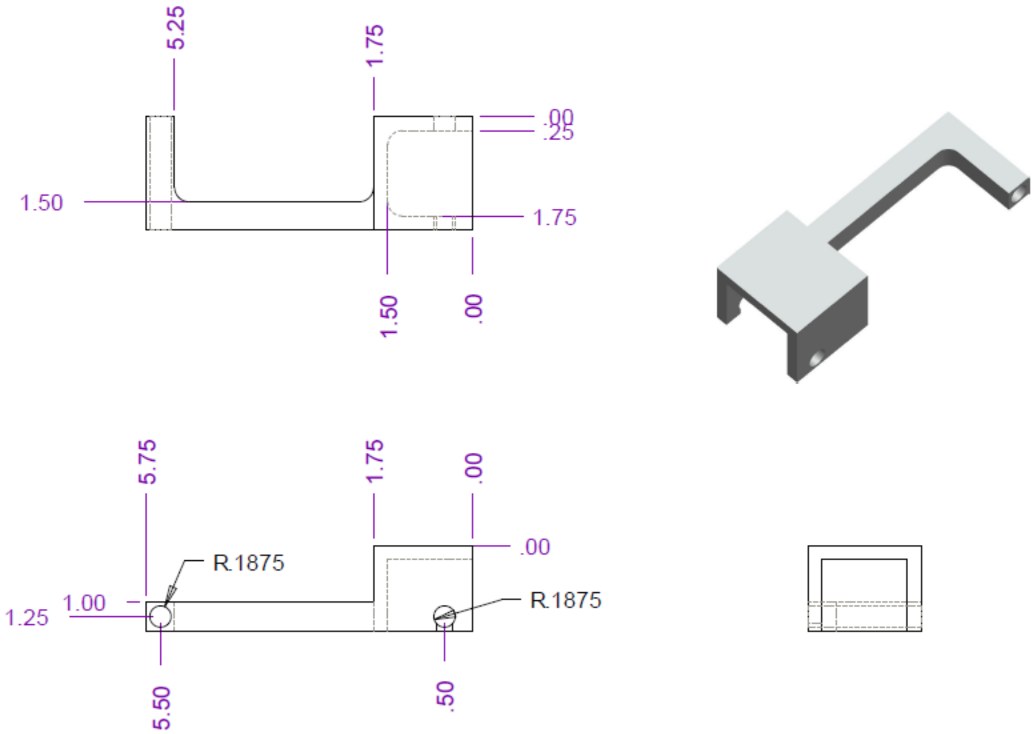


Figure F7. Follower Arm



1/2" End Mill, 3/8" drill

1) clamp on side, drill 3/8 holes through
2) clamp in upside down, mill out chambers (rear .55" deep)
3) clamp right-side-up, mill out upper profile
4) cut from original material, clamp and finish rear edge

Figure F8. Follower Idlers

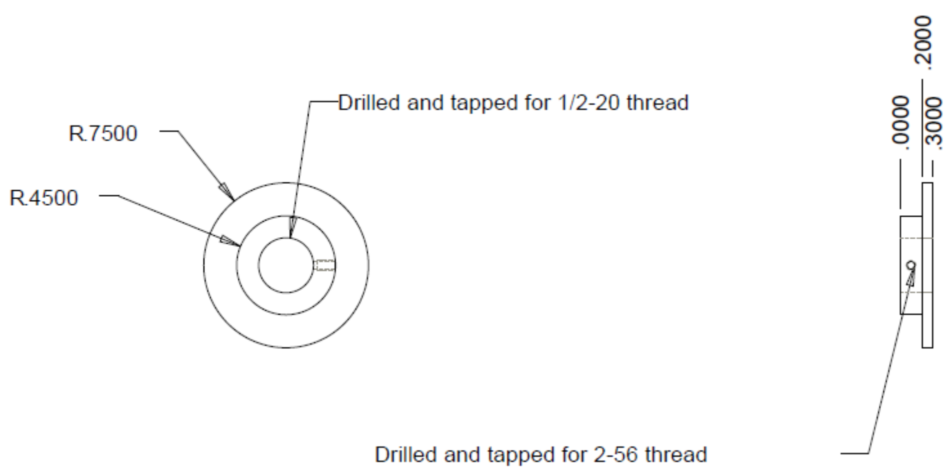


Figure F9. Roller Sideplate Shaft

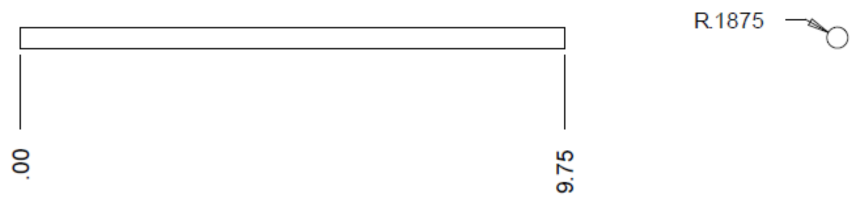


Figure F10. Boom

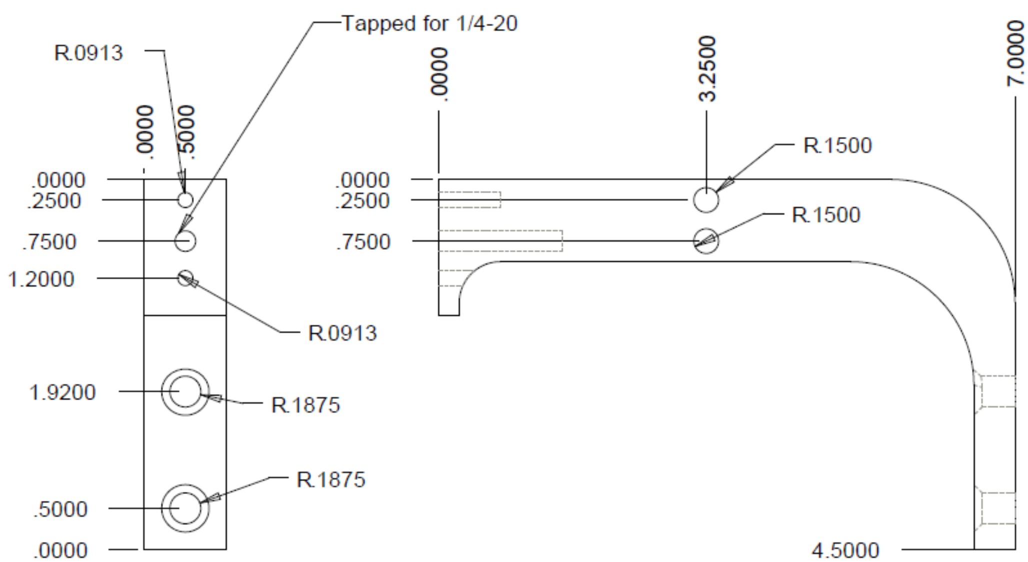


Figure F11. Roller Sideplate

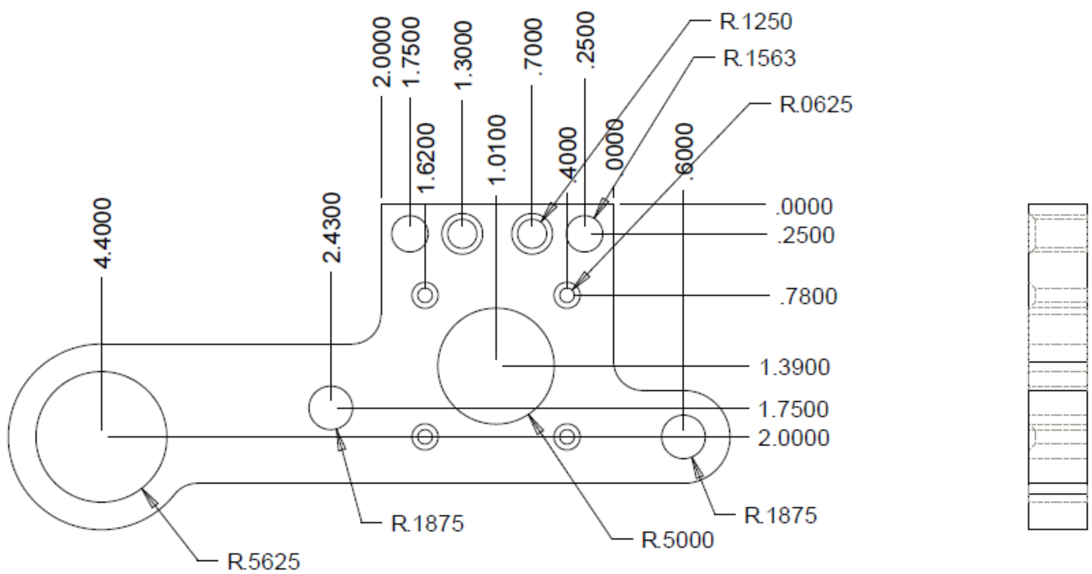


Figure F12. Roller Wings

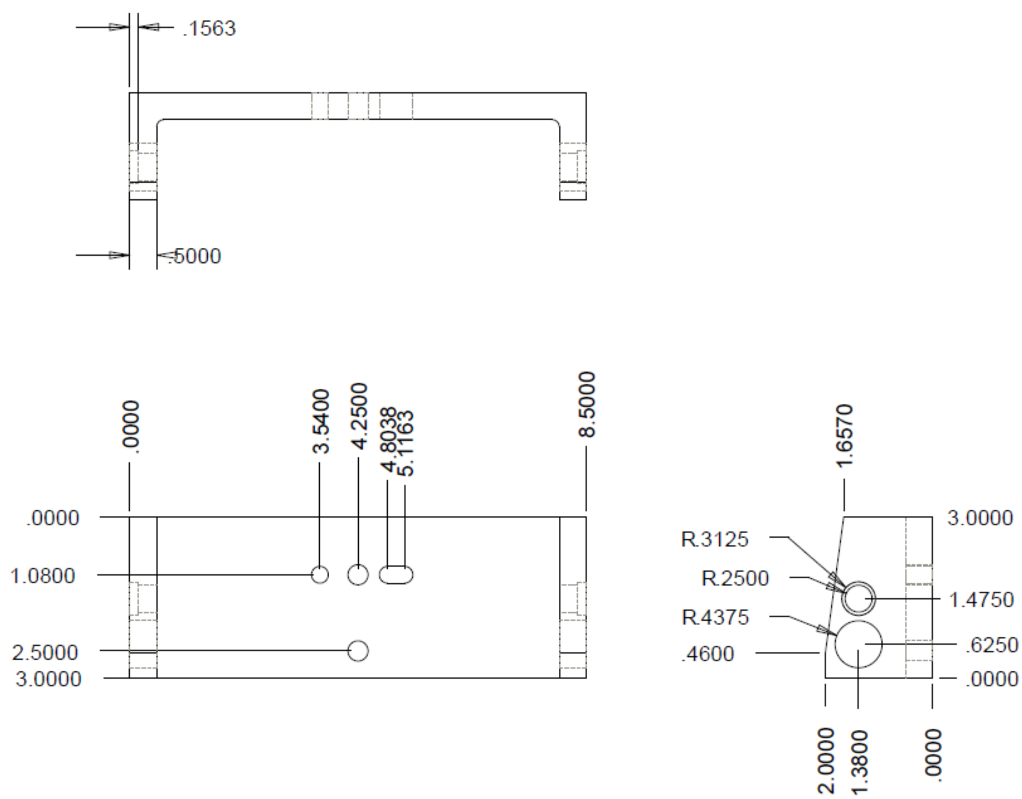


Figure F13. Sideplate Stabilizer

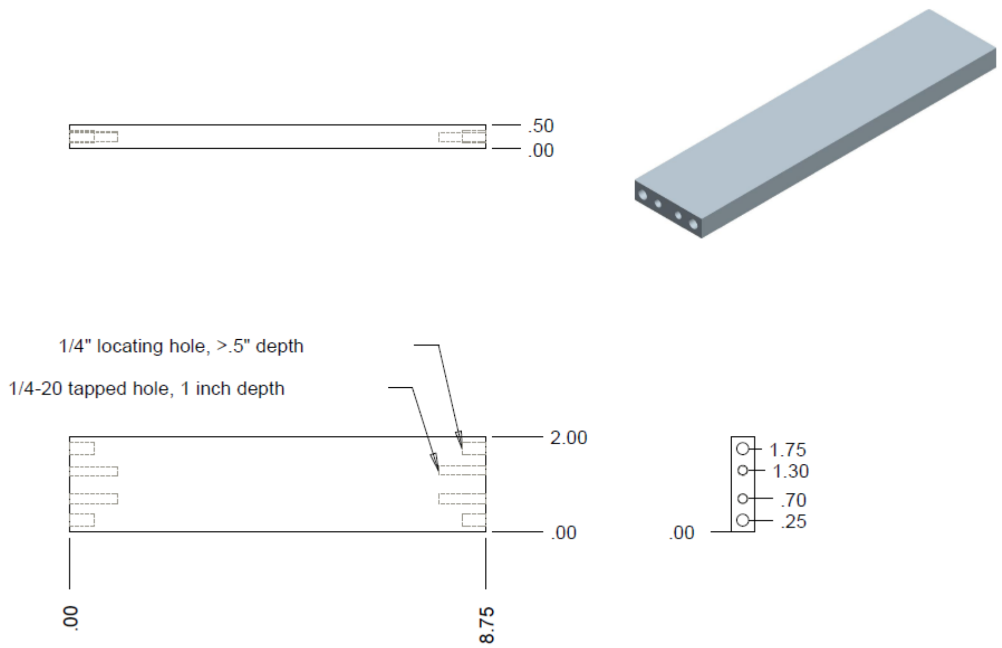


Figure F14. Spring Perch

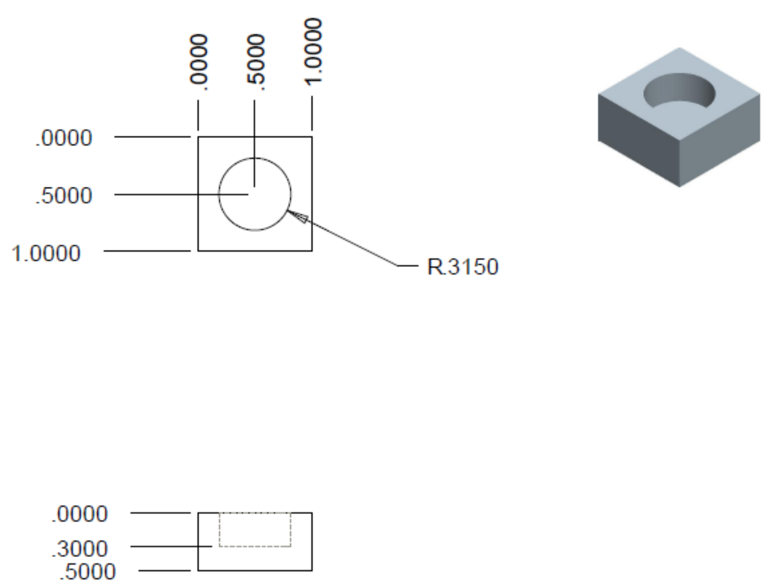


Figure F15. Toppler

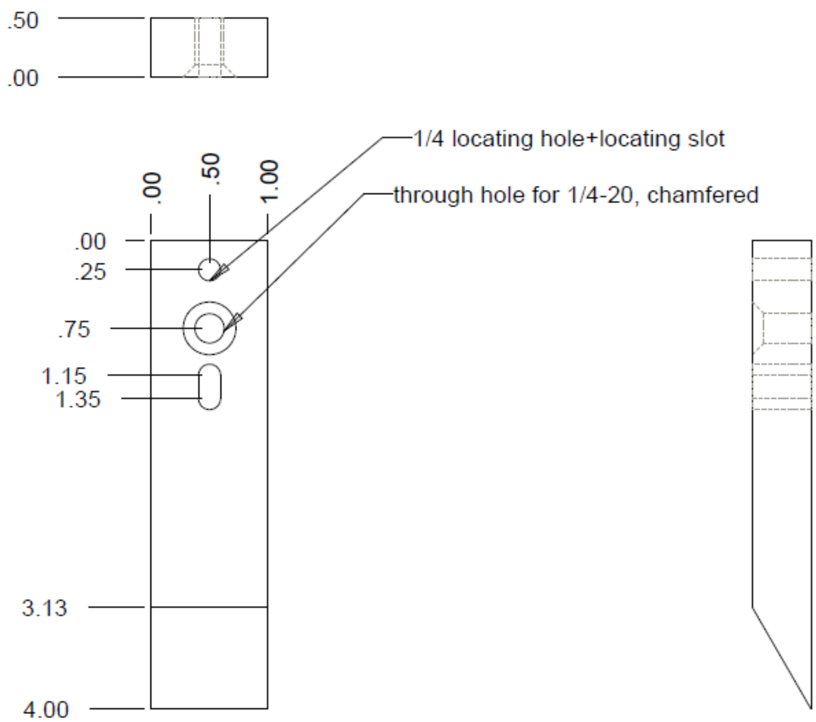
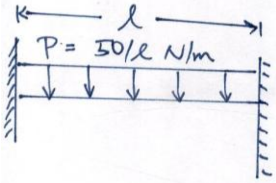


Figure F16. Transmission Shaft

APPENDIX G – MODELING

Figure G1. Roller Deflection



$$\text{Deflection} = \frac{Pl^3}{384EI}$$

Stainless steel : $E = 220$ GPa

$r = 0.6$ mm $= 0.6 \times 10^{-3}$ m

Quartz tube : $E = 72$ GPa

$r = 0.25$ mm $= 0.25 \times 10^{-3}$ m

Set $l = 1$ cm $= 0.01$ m , $P_{tot} = 50$ N.

Stainless steel = $I = \frac{16\pi r^4}{64} = \frac{\pi(0.6\times10^{-3})^4}{4} = 1.0179 \times 10^{-13}\, m^4$

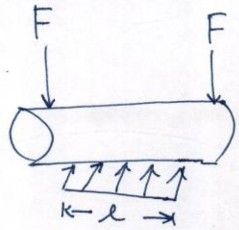
Quartz tube : $I = \frac{\pi r^4}{4} = \frac{\pi(0.25\times10^{-3})^4}{4} = 3.068 \times 10^{-15}\, m^4$

$$\text{Deflection}_{ss} = \frac{50(0.01)^3}{384(220\times10^9)(1.0179\times10^{-13})} = 5.8146\ \mu m$$

$$\text{Deflection}_{Quartz} = \frac{50(0.01)^3}{384(72\times10^9)(3.068\times10^{-15})} = 589.5\ \mu m$$

(100 times of deflection_{ss})

Figure G2. Roller Friction



	Stainless steel	Quartz
Shear strength	186 MPa	70 MPa
Static friction Coefficient	0.188	0.4

Assume 2F = 50 (the maximum force)

tainless steel : Torque = $T_{ss} = \mu_s (2F) r_{ss} = 0.188 (50) (0.6 \times 10^{-3})$

$= 0.00564 \ N \cdot m$

$$\tau_{ss} = \frac{T_{ss} \cdot r_{ss}}{J_{ss}} = \frac{(0.00564)(0.6 \times 10^{-3})}{\frac{\pi (0.6 \times 10^{-3})^4}{2}} = 16.62 \text{ MPa} < 186 \text{ MPa}$$

⇒ No yielding.

Quartz : Torque = $T_{Qu} = \mu_s (2F) r_{Qu} = (0.4)(50)(25 \times 10^{-5})$

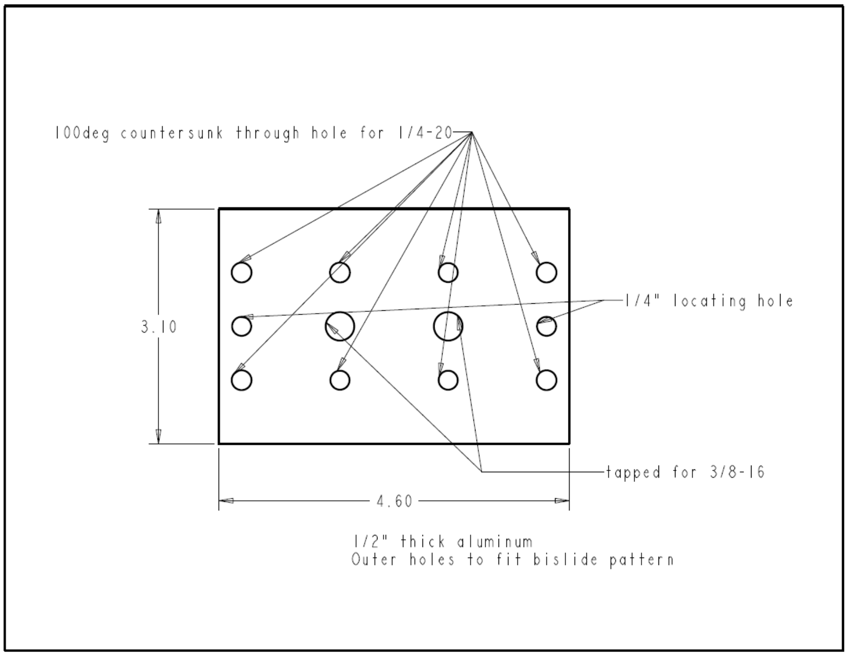
$= 0.005 \ N \cdot m$

$$\tau_{Qu} = \frac{T_{Qu} \cdot r_{Qu}}{J_{Qu}} = \frac{(0.005)(0.25 \times 10^{-3})}{\frac{\pi (0.25 \times 10^{-3})^{-4}}{2}}$$

$= 203.7 \text{ MPa} < 70 \text{ MPa}$.

⇒ The quartz tube provided from our sponsor would not work in this case.

APPENDIX H – EXAMPLE DIMENSIONED DRAWING



APPENDIX I – ENVIRONMENTAL IMPACT

Figure I1. Impact Characterization

Figure I2. Impact Assessment Normalization

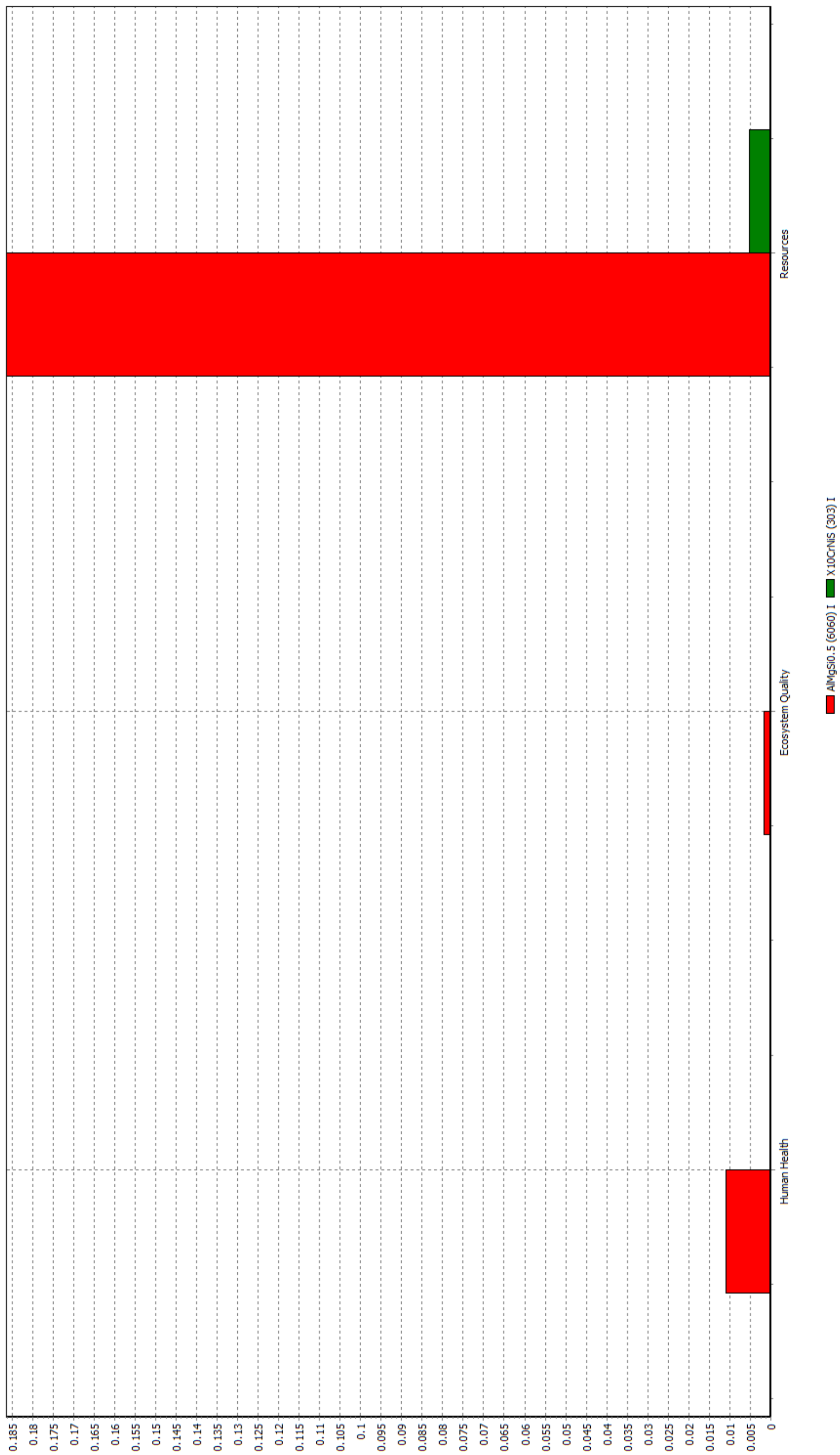
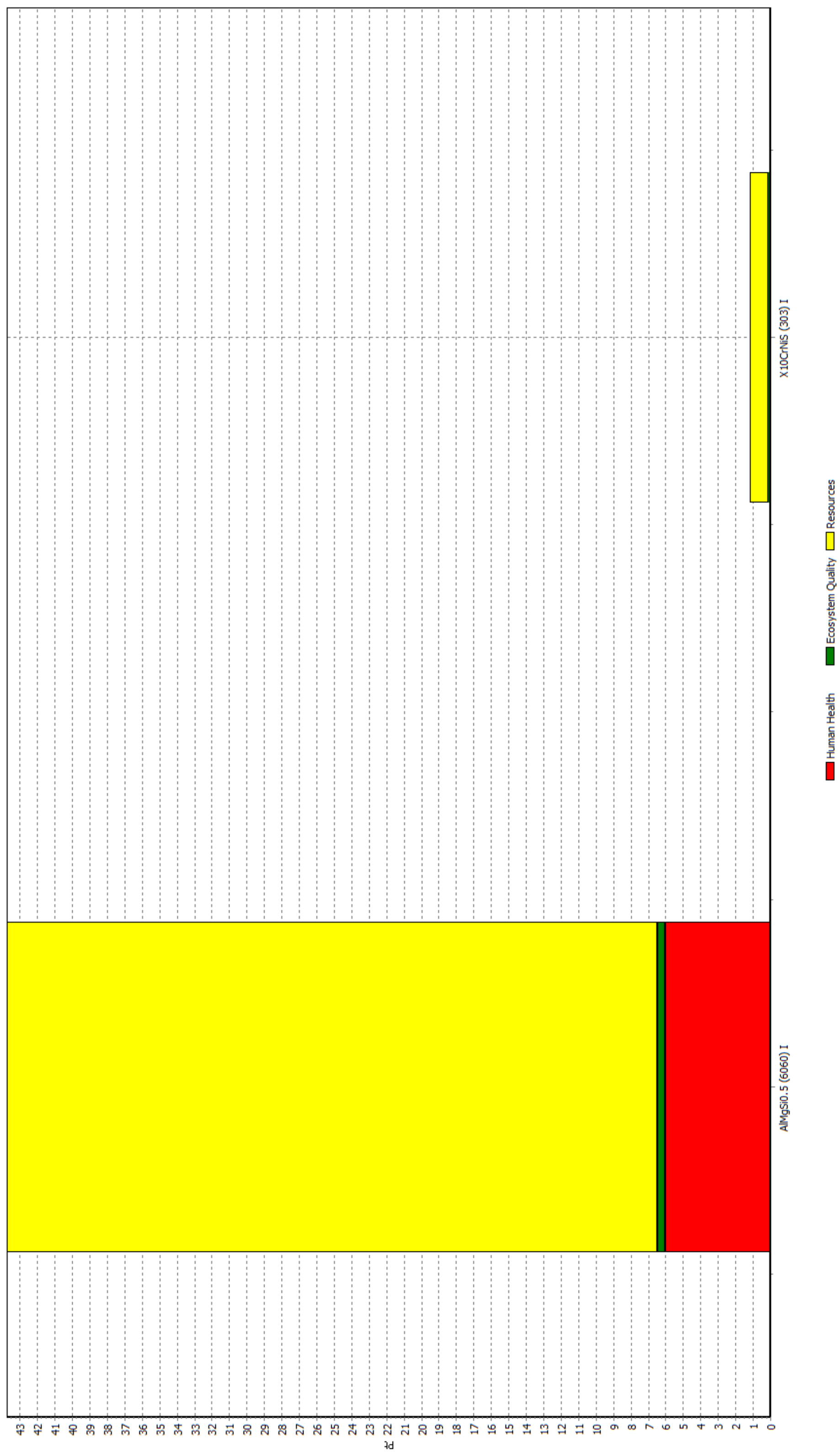
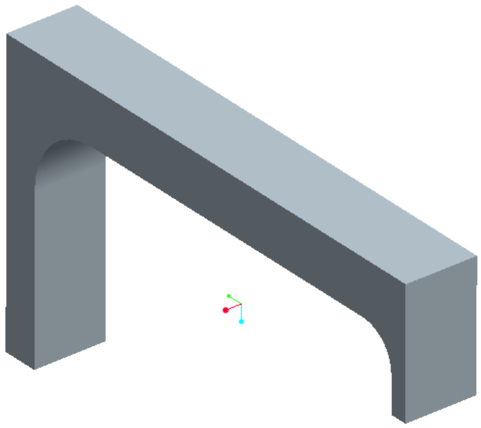


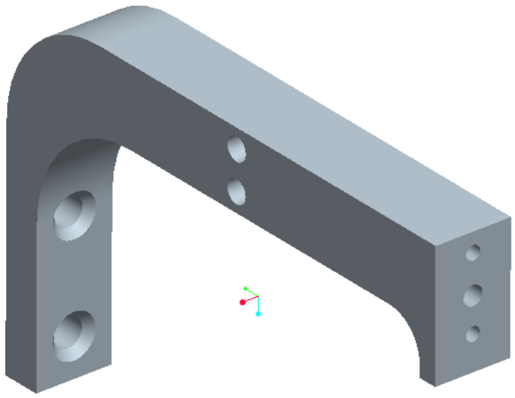
Figure I3. Impact Assessment Single Score



APPENDIX J – ENGINEERING DESIGN CHANGES

Part 4.1.2 Support Boom

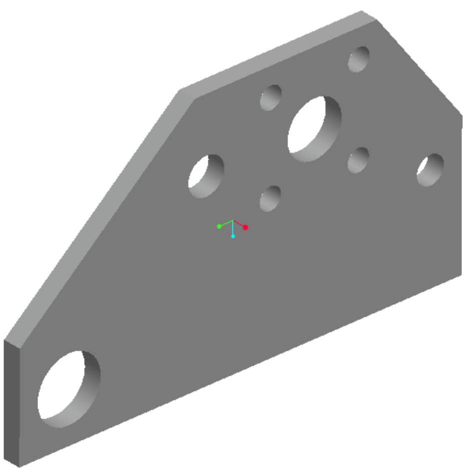


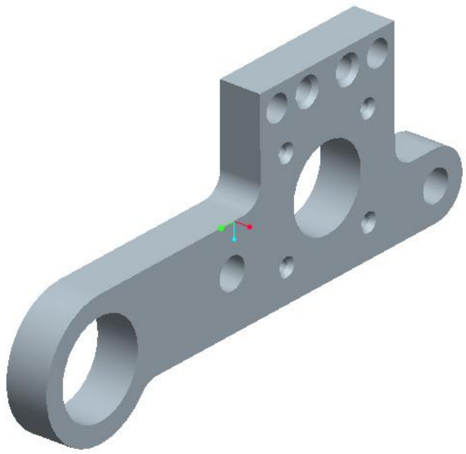


Original Design **Revised Design**

- Availability of water jet for fabrication allowed shape with more gradual transition from vertical to horizontal.
  - Increases part stiffness and aids in head accessibility.

Part 4.3.1 Roller Sideplate



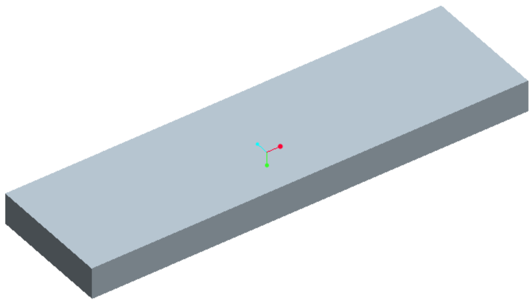


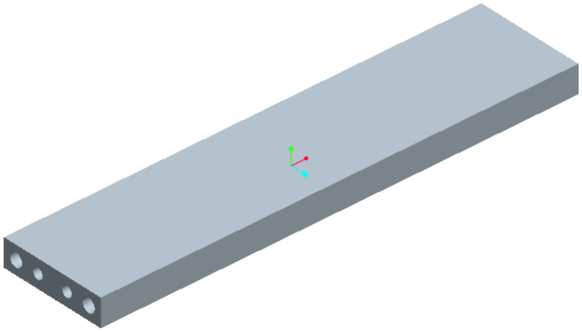
Original Design **Revised Design**

- Increased part thickness for more accurate press fit
- Utilized water jet for more complex outer profile
  - Decreased part weight
  - Increased head accessibility
- Relocated rear axle, front chuck centers

- More vertical alignment between idlers and roller through short travel

4.3.2 Roller Sideplate Stabilizer





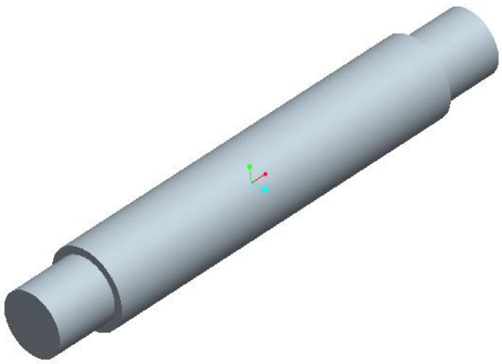
Original Design **Revised Design**

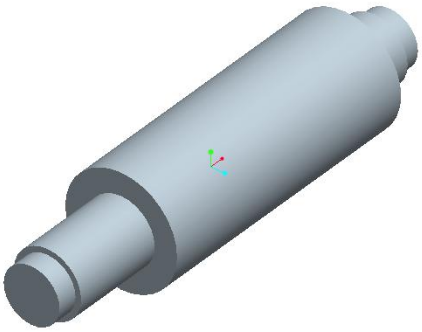
- Lengthened to accommodate outboard roller sideplates (4.3.1)

4.3.3 Roller Axle

- Lengthened to accommodate outboard roller sideplates (4.3.1)

4.4.2 Idler Shaft

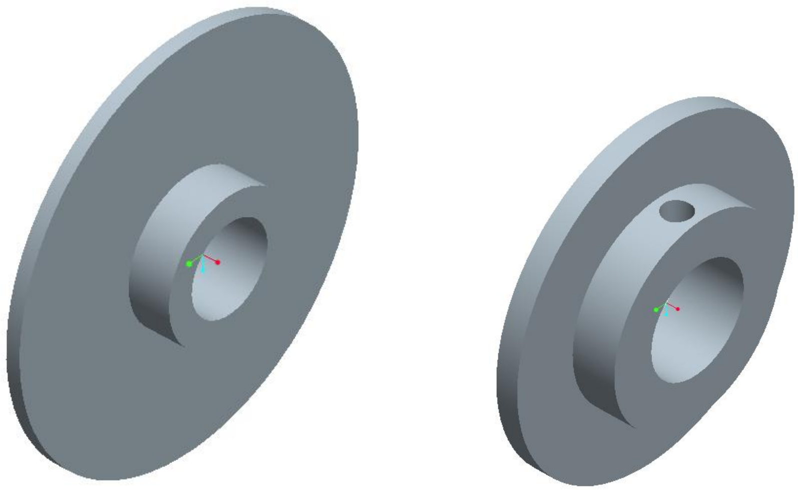




Original Design **Revised Design**

- Section of decreased diameter to allow assembly
- Shoulder to constrain lateral movement when assembled

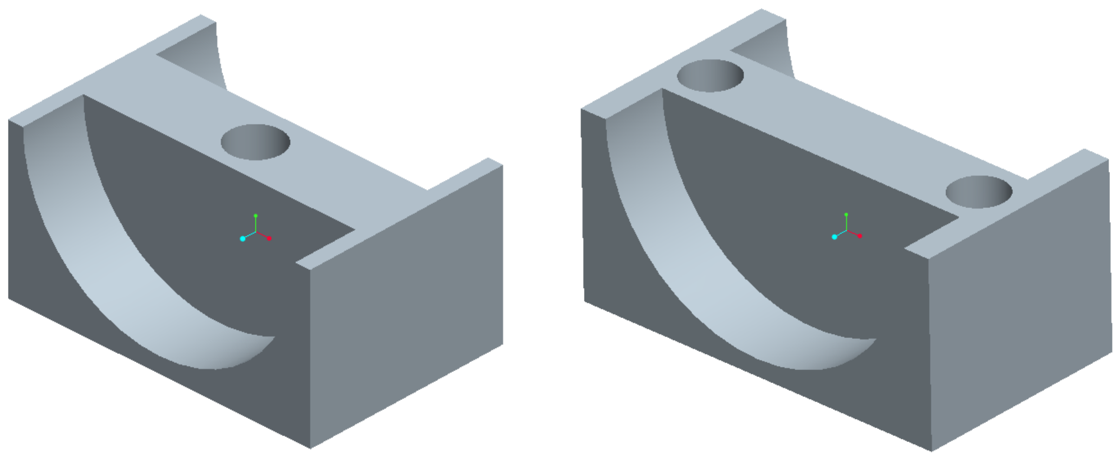
4.4.3 Idler



Original Design **Revised Design**

- Decreased diameter to allow assembly
- Add setscrew for reliable positioning

4.6.2 Flattener



- Decrease diameter to accommodate idlers
- Relocate machine screw hole to clear idler shaft

4.7.2 Torque Shaft

- Lengthened to accommodate outboard roller sideplates (4.3.1)