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#### ABSTRACT

## DESIGN AND FABRICATION OF A TAPPED DENSIFICATION APPARATUS FOR BULK SOLIDS

#### by Joshua H. De Jong

Experiments are commonly used to ascertain the flow properties of bulk solids. One such property is a measurement quantity known as the tapped density. Here, a container of granular material is subjected to a long sequence of discrete taps, after which the bulk density – the total mass divided by the volume occupied – is determined. Current technology exists to achieve the maximum tap density by subjecting a container to a user defined number of taps at a specific, predetermined amplitude and frequency. However, the final bulk density is known to be dependent on the tap parameters. It can therefore be beneficial to alter both the frequency and the amplitude during the experimental process to determine what role these two factors contribute to the tap density of a sample. Thus, the topic of this thesis is the design, fabrication and testing of a mechanical system device that allows for finite control of the tap stroke and force, as well as quantitative measurement feedback for the motion of the sample.

The first phase of the work consisted of the design and fabrication of a prototype system, which was tested for the proper functioning of the mechanical components. The results of the tests suggested modifications were required. A series of revisions were preformed on the prototype in order to satisfy the updated design requirements. Final tests and calibrations were preformed on the new apparatus and the results are discussed.

## DESIGN AND FABRICATION OF A TAPPED DENSIFICATION APPARATUS FOR BULK SOLIDS

by Joshua H. De Jong

A Thesis Submitted to the Faculty of New Jersey Institute of Technology In Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

**Department of Mechanical and Industrial Engineering** 

January 2011

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## **APPROVAL PAGE**

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To my wife, my daughter, and my family. Without any of these, none of this would be possible.

#### ACKNOWLEDGMENT

I would like to thank Dr. Anthony Rosato for his choice in commissioning me to design and build this project. His guidance, patience, funding and help have been instrumental in allowing me to complete this assignment. I would like to thank the committee members, Pushpendra Singh, Ian Fisher and I.J. Rao for taking their time to deem my work acceptable. Special thanks also goes out to Fredrick Schumacher, President of Glebar Co., Inc., for his donation of most of the materials used in constructing the machine, as well as the allowed use of all the resources of the machine shop and engineering department at Glebar. Thanks to Robert Gleason, Vice President of Engineering, Glebar Co., Inc. for his encouragement and help in the manufacturing of the finished prototype.

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# LIST OF SYMBOLS

a	Acceleration $(in/s^2)$
А	Area (in <sup>2</sup> )
d	Cylinder Bore Diameter (in)
F	Force (lbs)
G	Gravitational Acceleration (386 in/s <sup>2</sup> )
KE	Kinetic Energy
m	Mass
Р	Pressure (lbs/in <sup>2</sup> )
PE	Potential Energy
S	Distance (inches)
V	Velocity (in/s)
W	Weight (lbs)
π	Pi (3.14159)

#### **CHAPTER 1**

#### INTRODUCTION AND LITERATURE SURVEY

#### **1.1 Introduction**

The study of granular motion is important for many industrial applications. Pharmaceuticals and food production are two of the main industries that use granular motion to handle product. Because of this, it is important to study how particulate matter interacts with its environment.

To study the effects of granular dynamics, valuable property to study is called the bulk density or tapped bulk density. This is a property relating the effects of a dynamic tapping motion upon a container of granular particles. The density of granular particles relies on the size and shape of the particles, as well as how closely these particles are packed together. As the container of granular particles is tapped, the smaller particles tend to fill in the spaces between the larger particles. This causes the density of the bulk as a whole to increase.

The bulk density is reliant on many factors. The number of taps, force of tap, total height change during the motion, as well as any geometry between the container and the particles themselves all play an important role in determining how quickly and tightly the particles pack together.

#### **1.2 Current Industry Solutions**

There are many ways to test tapped bulk density. Industry standards range from manual tapping of a cylinder with granular particles, to fully automated solutions that measure dynamic flow of granular particles as they travel through feeding systems.

Manual tapping involves placing the granular particles in a container and hitting the bottom of the container multiple times. This approach is the simplest method, but does not allow for accurate data collection. While the number of taps, and the final bulk density are known entities, tap force and height are not easily repeated over the course of an experiment. As such, this method is really only useful in studying the effects of tapping in general, and the dynamics of the packed material after the experiment is complete.

Due to the inaccuracies inherent in the manual tapping method, more robust, automated systems were designed. One such solution is a product from Quantachrome (Quantachrome, 2010). Quantachrome is a manufacturer of laboratory testing equipment. Their tap density offering consists of a product named the Autotap. This device taps a pre-determined number of times on a container filled with granular materials. The height of the tap is fixed at a standard 3mm, and the force of the taps is also kept constant. Manufacturer specifications state that this device can tap up to 260 times per minute with as many as 9999 taps. The value of the Autotap is derived from its fast tapping rate, and the fact that height and force are kept constant. This allows for fast experimenting with many different types of materials and particles, and allows the experimenter to easily compare the results from many samples in a controlled environment.



**Figure 1.1** Quantachrome AutoTap and Dual AutoTap. **Source:** (Quantachrome, 2010)

Another device used to measure tapped density is available from Antech (Antech, 2010). Their JV series tapped density tester works very similar to the Quantachrome for determining the tapped density. The device lifts the sample a pre-determined height using a rotating cam, then drops the sample, allowing it to free-fall down to the surface of the test device. Again, the height and force is pre-determined for each sample as the force is a function of the gravitational acceleration. The only variable in this is the fact that different solids will have different mass, so the force exerted on the granular material will change with the type of material and the amount of material used.



**Figure 1.2** Antech JV Series single and double station tap density measurement devices. **Source:** (Antech, 2010)

Similar devices can be bought from many different place. These typically handle either one or two testing stations and operate using a motorized cam shaft rotating at specific speeds. As the cam rotates, it lifts the sample into the air, then allows it to drop at the rate of gravity. Distek produces a two station tap-density tester called the TD-1020 (Distek, 2010). Sotax currently has the TD1 Tap Density Tester (Sotax, 2010). Varian, also known as Agilent, also produces a version of this device called the Tapped Density Tester 70-9010 (Varian, 2010). Electrolab produces ETD-1020 (Electrolab, 2010). All of these devices function in a similar fashion. Differences between the device range from user input methods to printable data reports. Many of them support two methods of obtaining the maximum tapped density: Either by running a standard tap test for a predetermined number of taps or allowing a user input value of taps to determine the number of taps required to obtain the tapped density for each material. In most cases, these tap density testers are sufficient for the needs of the general industry. Many laboratories do not necessarily need to know the best method to obtaining the maximum tap density, just a consistent, repeatable method to find it. In order to study the dynamic nature of obtaining the tapped density, a new type of device is required. Studying how the particles move during the tapping process and the effects of external variables on their motion may provide valuable insight into not only the best ways to obtain the tapped density, but also how the flow of the particles determines the tap density.

#### **1.3 Objective**

This thesis will provide an in-depth record of the design and manufacturing steps used in building a tapped densification apparatus. The primary focus of this paper is to document the process. The device will provide a basis for laboratory experiments that will allow scientists and engineers to alter test parameters in ways that have previously been absent in other tap density testing equipment.

#### 1.4 Thesis Outline

The remainder of this thesis is as follows. Chapter 2 starts by providing an in depth look into the design and manufacturing of a prototype tap density test device. It ends with the device testing and a brief overview of the changes that were deemed necessary. Chapter 3 describes the redesign and revision of the tap device to better meet the requirements and feature requests for the device. Chapter 4 begins by analyzing the test results of the

completed tapping device. It ends with an analysis of future improvements that can be implemented to further enhance the test device.

Appendix A is the assembly drawings used in building both the prototype and the revised version. Appendix B contains all of the multi-view engineering drawings used to manufacture the components. Following this is the schematics for the different systems used in the device. Appendix C contains a pneumatic schematic and Appendix D is the detailed electrical diagrams. Appendix E contains the source code for the controller for documentation completeness, and Appendix F is the instruction manual that is to be used for maintaining the tapped densification device. A list of vendors is also included in Appendix F.

#### **CHAPTER 2**

## THE PROTOTYPE

The object of this design was to build and test a working tapping device for experimenting with the tap density of bulk solids. To that end, an initial prototype was developed to meet specific needs of the experiments. As discussed in the previous sections, this device is essentially a new way to quantify the dynamic variables to obtaining the tapped density of granular materials.

#### 2.1 Design Criteria

Prior to any design work, it was necessary to determine the design criteria that the project should encompass. The initial qualification was to build a machine that could deliver a vertical impulse to the bottom of a sample of bulk solids. Different methods of delivering the impulse, the delivered force and duration of the impulse, and device boundary conditions were all discussed in detail prior to any design work.

The first and most important goal of the project was to be able to achieve a variable tap force and stroke. This was necessary as to not only distinguish the machine from current industry solutions, but to allow for great flexibility in the experimental procedures that the machine was to be used for. This meant that any impact device must either be easily changeable or adjustable to achieve different forces and strokes as needed. The direction of the impulse was to originate at the bottom of the test sample, forcing it up into the air and allowing a free-fall motion back to the original starting position.

The next design request was that the test sample remains in the same orientation throughout its entire motion. This meant that the only allowable degree of freedom was in the vertical axis. A suitable solution needed to be researched in order to provide maximum freedom in this axis while prohibiting motion in the others. The desired minimum target for a maximum stroke in the vertical axis was 1-1/8". The device had to be at least capable of propelling a test sample that distance.

The design constraint limiting the motion to a single axis requires that the device hold both the sample and the impact device in the same vertically oriented axis. To ensure this requirement in various testing environments, it was determined that some sort of leveling system would need to be designed in order to guarantee that a large amount of surface gradients and slopes could be accounted and compensated for.

When sample containers were discussed in the brainstorming stage, it was determined that material was already available to use. The sample containers were to be made out of acrylic tubing. The maximum diameter of this material was to be 3". The machine needed to be able to handle any size cylindrical test sample container up to this diameter.

One of the more complicated requirements was fundamental to the nature of the test apparatus. Some sort of sensory feedback needed to be implemented in order to determine the distance, velocity and acceleration profiles of the cylinder through the entire range of motion. This could be done in any number of ways, and calculation of some components was deemed allowable, but in order to achieve this, accurate sample readings must be obtained through the application of the impulse and the sample settling time.

Lastly, the device was to be designed with a collegiate laboratory in mind. This meant budgetary constraints were placed on the project both for the initial design, and for the life of the machine. Materials and replacement parts needed to be cost effective and readily available should mechanical failure or user error cause the machine to cease proper function. While no direct monetary value was placed on the budget, it was determined that the system should use industry standard components for maximum reliability and cost reduction. The final design points are summed up in Table 2.1.

 Table 2.1
 Prototype Design Criteria

	Criteria
1.	Variable impact stroke
2.	Variable impact force
3.	Motion constrained to a vertical axis
4.	Vertical sample stroke of 1.125"
5.	Ability to ensure a level test surface for the device
6.	Maximum test sample container size 3" diameter
7.	Sensory feedback for test analysis

## 2.2 Design Stage

In the design stage, each of the previous points was evaluated and solutions were sought.

The following sections describe how each of the items was dealt with in the design phase.

#### 2.2.1 Variable Impact Stroke and Force

The first two design criteria were taken as a single problem. Finding an impact device that would solve both of these problems was very simple. A solenoid is an industry standard component that takes energy in the form of air, fluid or electricity and uses it to create a linear force.

In the scope of this project, hydraulic (fluid) solenoids were eliminated from the start. These provide a very reliable application of force, but require pumps, tubing, and can be prone to leaking. Hydraulic pumps are often loud and cumbersome, as well.

Electronic solenoids were explored, but due to severe time constraints to complete the work on the initial prototype, not enough research could be completed to find a suitable solution that would allow for a variable impacts and strokes, as well as provide a cost effective solution to the situation.

Therefore, an air solenoid was chosen as the actuating device. Air compressors are an integral part of many laboratories, and those without can easily overcome this by a small, portable compressor available at any hardware store. Air solenoids are clean, efficient, and have been tested for hundreds of thousands of cycles. They can also be very inexpensive and most standard sizes are usually in stock ready for delivery. An air cylinder with a 1" stroke and 1" bore diameter can easily be purchased for under \$60.

Most importantly, air cylinders also fulfill the requirements of variable stroke and force. The force an air cylinder exerts on an object is directly proportional to the pressure of the air introduced into the cylinder body. It is a function of the air pressure applied to the system and the diameter of the bore in the cylinder.

$$F = PA \tag{2.1}$$

$$A = \frac{d^2}{4}\pi\tag{2.2}$$

$$F = \frac{\pi}{4} P d^2 \tag{2.3}$$

In Equation 2.1, force on the cylinder piston is equal to the pressure multiplied by the area of the piston bore. Equation 2.2 is the known area of a circular surface, and Equation 3.3 is made by substituting this into Equation 2.1. If the diameter of the cylinder bore is a fixed 1", then the result can be calculated based on this value.

$$F = .785P$$
 (2.4)

The value of P is in units of pounds per square inch. To alter the force delivered by the cylinder, a pressure gage can be inserted immediately after the air source providing pressure to the line.

For the variable stroke, there are two ways to change this parameter. The first is to change the height at which the sample container rests above the stationary air cylinder. The second method is to vary the stroke of the air cylinder itself.



**Figure 2.1** Diagram of the two variables in the test apparatus stroke. The sample height can be altered, as well as the stroke length of the air cylinder.

The easiest adjustment to make is the sample height. Simply altering the stop at which the sample rests in relation to the air cylinder changes this height. Most air cylinders, however, do not have a variable stroke in a single air cylinder. Air cylinders do have the advantages of being inexpensive and easily mounted. This means that multiple air cylinders with different strokes can be purchased cheaply, and swapped in and out of the test apparatus with relative ease.

## 2.2.2 Constrain Motion to a Vertical Axis

The motion of the test sample needed to be constrained to a single, vertical axis. This meant that a system of rails needed to be designed in order to limit mobility on the horizontal plane as well as any torsional motion. These rail systems come in all shapes

and sizes from low-friction gliding carriages and track assemblies, all the way to ball and air bearing linear guide systems.

Without proper tools and experience, building rails from raw materials can be very challenging. It can also be cost and time prohibitive. For these reasons, most times it is easier and far more reliable to settle on a purchased product instead of trying to design and machine a custom solution. Various companies do a wonderful job handling the precise manufacturing and assembly that is required to make linear rail systems.

## 2.2.3 Vertical Sample Stroke of 1.125"

The next goal was to ensure the device could project the sample at least to a height of 1.125" from rest. To do this, two things need to be determined: the first is the length of the rail that was selected, and the second is the force required to propel the sample and its container to that height.

For the rail length, because this was going to be a purchased component, simply checking the product manual for the stroke and carriage lengths would easily fulfill this need. Most companies that specialize in linear rail systems include calculations for determining the required length to purchase. This is usually in some form of Equation 2.5.

$$Length = Stroke + Length of Carraige + C$$
(2.5)

The parameter C represents some constant value, usually pertaining to a fixed length of end stop or unusable rail. Most manufacturers will list this value in their manual if it is required. To calculate the force required to move an object of weight, W, it is necessary to perform some calculations. Figure 2.2 will be used as a reference in explaining the calculations performed.



**Figure 2.2** Diagram depicting motion of the sample. Position A is at  $t_0$ . The piston exerts a force on the sample, lifting it into the air. At position B, the piston motion reverses, and the sample continues traveling upward. Position C depicts the sample container reaching maximum height.

The first calculations was to determine an equation for the velocity,  $V_B$ , and acceleration, a, when the force is removed.
$$F - mg = ma \tag{2.6}$$

$$m = m_{sample} + m_{piston} \tag{2.7}$$

The mass of the piston compared to the mass of the sample is assumed to be negligible, so m is assumed to be the mass of the sample alone.

$$a = \frac{F - mg}{m} \tag{2.8}$$

$$V_B^{\ 2} = V_A^{\ 2} + 2a(S_B - S_A) \tag{2.9}$$

$$V_B{}^2 = 2aS_B \tag{2.10}$$

The paramaters  $S_A$ ,  $S_B$ , and  $S_C$  describe the distance the sample has traveled at each point in Figure 2.2.  $S_A$  is set as 0 in this instance,  $S_B$  relates to the stroke length, and  $S_C$  is the maximum height the sample container reaches before falling back to the point  $S_A$ . Once the sample container and piston reach point B, the piston drops down. The sample has a momentum, and a velocity traveling upward. It is also being subjected to the force of gravity pushing down. Conservation of Energy is then used to determine the distance the cylinder travels based on the velocity at point B.

$$KE_B + PE_B = KE_C + PE_C \tag{2.11}$$

$$\frac{1}{2}mV_B{}^2 + 0 = 0 + mgS_C \tag{2.12}$$

The potential energy at B is assumed to be zero. At point C, the maximum height has been reached, and velocity and acceleration both reach zero, so the kinetic energy at C is also assumed to be zero. A substitution of (2.10) into (2.12) yields:

$$\frac{1}{2}m(2aS_B) = mgS_C \tag{2.13}$$

$$aS_B = gS_C \tag{2.14}$$

$$\frac{F - mg}{m}S_B = gS_C \tag{2.15}$$

Equation 2.15 is now in terms of force, mass, and predetermined distances. The next step is to isolate this force and obtain an equation based on weight, instead of mass.

$$\frac{F - mg}{mg}S_B = S_C \tag{2.16}$$

$$FS_B - mgS_B = S_C mg \tag{2.17}$$

$$F = \frac{S_C mg + S_B mg}{S_B} \tag{2.18}$$

$$F = mg\left(\frac{S_C + S_B}{S_B}\right) \tag{2.19}$$

$$W = mg \tag{2.20}$$

$$F = W\left(\frac{S_C + S_B}{S_B}\right) \tag{2.21}$$

 $S_C$  represents the elevation of point *C*, which is predetermined as a design requirement of 1.125 inches.  $S_B$  is the distance that the force acts on the plate. One of

the design requirements of this project is to make this a user-defined value. For evaluation's sake, SB will be set to a small value of .1". The sample weight will be estimated at around 5 lbs. Inserting these numbers into Equation 2.21 revealed a required force of 61.25 lbs. Using Equation 2.4, the pressure required is 78 psi. Most industrial air sources handle between 80 and 120 psi, so the design requirement should easily be met.

## 2.2.4 Ensuring a Level Test Device

It was important to be able to constrain the motion vertically. To do this, the device needed to have the ability to level the main operating mechanisms. It was determined that the simplest way to achieve this was to split the base into two sections. The lower section would rest on a solid surface, while the upper section would incorporate leveling feet in order to maintain proper trim. It was also necessary to secure the two sections together during operation, as the air cylinder could exert enough momentum on the upper surface to shift its position.

## 2.2.5 Maximum Container Size of 3" Diameter

The constraint on the maximum size of the sample container limited the size necessary for the device. It also meant that the total mass of the sample could be kept small, keeping the range of the air cylinder relevant. By keeping the sample container at 3" or less, the size of the surface needed to hold the cylinder during motion could be kept down, reducing extra weight.

#### 2.2.6 Sensory Feedback for Test Analysis

In order to provide sensory feedback, some form of automated data capture system was needed. This meant the control system for the test apparatus needed to be able to control the air cylinder activation as well as handle incoming analog or digital signals from some sort of sensors. For the prototype design, an accelerometer was chosen in order to measure the acceleration during the entire motion of the test sample. A height scale was also chosen to allow a user to be able to determine just how high the sample traveled during the motion. These two values could then be used to determine the entire motion profile during each tap.

## 2.2.7 General Function and User Interface Analysis

The last steps of the design analysis stage were to determine how the user would interact with the device, and subsequently, how the functionality would be implemented to automate a test process. The device required an accelerometer, so some sort of analog data capture would be required, as well as some way for a user to initiate a tap. More importantly, the device was designed to determine the effect of multiple taps on the density of bulk solids. This required some sort of automation in order to prevent a user from having to manually push a button or switch for each tap.

To this end, a manual push button for taps would need to be designed, as well as a switch that could be left in position to automate taps. Some sort of timing circuit would need to be implemented in order to determine when the next tap should take place, in case the frequency of taps needed to be variable. It was also decided the best method for handling the electronics would be a microcontroller. Microcontrollers are an inexpensive, effective way of handling many configurations of digital inputs, digital outputs, and analog inputs. This made the electronics a lot simpler than custom circuitry.

## 2.3 Prototype Build

After the initial design requirements were analyzed and the force and pressure requirements were calculated, it was necessary to develop and build the actual device. To this end, Autodesk Inventor was used extensively for the design of the parts themselves. Throughout the next sections, most of the figures were all created using this incredibly powerful tool. All of the assembly drawings for the prototype can be viewed in Appendix A, Section 1, while the individual part drawings used to manufacture the components are shown in Appendix B, Section 1.

When designing the parts, material selection became an important decision. In this particular project, many of the materials used in the actual construction of the prototype were donated by Glebar Co., Inc. Raw materials, fasteners, and the air components were all donated to the project. They also provided invaluable help when the actual machining was being performed.

Due to the fact that raw materials were donated, aluminum was chosen as the primary material for the prototype. The relatively low forces involved in this device meant that aluminum would be more than sufficient to handle the structural aspect of the device. Aluminum is also very easy to machine, can have many different types of finishes applied from paint to powder coat to anodizing, and Glebar had a large stock of smaller aluminum sections that were available for the project. In a few instances, where noted below, alternate materials were chosen.

# 2.3.1 Tapping Platform

The first concept examined in the system was a platform to hold the sample containers. This was designed as a simple, thin plate with a second plate that acted as a clamp for the sample container.



**Figure 2.3** Tapping platform and container clamp. The clamp fits over the top of a sample container and four screws are used to lock it onto the tapping plate.

## 2.3.2 Rail Selection and Implementation

The rails selected for the prototype were from IGUS Corporation. Their DryLin N product line is a low-friction linear carriage that slides through an aluminum extrusion. These were selected for their low cost, smooth motion, and low profile.



**Figure 2.4** Multiple views of the DryLin N linear rail assembly. **Source:** (IGUS, 2010)

One of the disadvantages to such a low cost rail is that they do have a bit of play in the aluminum extrusion due to fairly loose fits and tolerances, so four rails were selected, one for each corner of the tapping platform to help maintain stability. To secure the platform to the rails, four mounting brackets were designed, along with four tall pillars to secure the aluminum extrusion to.



Figure 2.5 View of the assembly of one of the 4 main corner posts and rails.

Flat head screws were used to attach the aluminum rail to the support post. This kept the screw head from interfering with the motion of the carriage. Stop pins were press fit into the support post to provide upper and lower limits to the motion of the carriage. The force exerted by the air cylinder had the ability to push the sample much higher than the tests required if the pressure was not set correctly.

# 2.3.3 Height Verification

Attached to the front, left side post of the device was a scale. This was to be used to determine the height that the sample traveled during the test. The original idea was to use a high speed camera to capture the tests in real time, and then use the scale to visually inspect the height at each frame the camera captured. A reference marker was added for clearer visual observation.



Figure 2.6 Exploded view of left wall for assembly of rail and trucks.



**Figure 2.7** Front view of the device showing the scale and reference marker used for visual inspection of test sample height.

# 2.3.4 Wall Construction

Up until this point, most of the components designed were primarily to provide

functionality to the device. Once the posts were designed it became necessary to develop

a better support structure to keep the tapping plate in its intended position.



Figure 2.8 Assembled view of leveling plate, walls, and corner supports.

Walls were designed to fit in between the posts. The posts were then attached using machine screws. A rear wall was affixed as a starting point for mounting a fixture to hold the air cylinder in place. The left and right side walls were designed to attach to a lower plate which would eventually become the upper section of the leveling system.

## 2.3.5 Dovetail Fixture

As shown back in Figure 2.1, the two ways to adjust testing stroke are to adjust either the physical stroke of the piston, or the height at which the piston contacts the sample. Changing the piston stroke is as simple as installing a cylinder with a different stroke, but stocking many different cylinders may not be the best solution. Instead, more thought was given to a method to be able to adjust the gap between the piston at rest and the tapping plate.

Since the tapping plate's rest position is fixed on the dowel pin, changing that position became impractical. Instead, it was easier to design height adjustment directly into the air cylinder mount. This was done by creating a dovetail fixture to attach to the rear wall. The vertical dovetail fixture provides adjustment and support for the air cylinder.



**Figure 2.9** Dovetail exploded view detailing assembly of clamp screws and mounting to rear wall.

The dovetail gave the air cylinder the ability to move in the vertical axis for adjustment of the tapping stroke. However, once the distance was set, the dovetail position needed to be locked in order to maintain that distance throughout the test. To inhibit motion during testing, two clamp screws were placed through a slot in the rear of the stationary dovetail block, and threaded into the sliding dovetail block. Tightening of these screws locks the sliding dovetail block into position. Figure 2.10 shows the crosssectional view of the dovetail assembly.



Figure 2.10 Dovetail cross-section depicting clamping screws in locked position.

## 2.3.6 Air Cylinder Mount

The particular cylinder chosen for the prototype is a Bimba EF1 type cylinder. This is a low-profile extruded cylinder that is low cost, easy to mount, and very reliable. The expected service life on an EF1 cylinder is 2500km of travel (Bimba, 2010). To provide a strong supply of air to the cylinder during its operating cycle, <sup>1</sup>/<sub>4</sub>" quick release air fittings were used.



Figure 2.11 Air cylinder mounting assembly, exploded view.

The air cylinder is bolted to a mounting plate that attaches directly to the sliding dovetail block. The mounting plate is constructed so that it provides a sturdy, perpendicular surface to the vertical axis. This helps to keep the cylinder in line with the vertical axis at all times, with very little deflection.

A bumper was designed to absorb the impact of the air cylinder on the tapping plate. Metal-on-metal contact leads to premature wear and tear on tapping plate, as well as shortening the life of the air cylinder. To this effect, a bumper was created from Vespel. It is a proprietary type of plastic known for its strength and durability. This protects the aluminum components from deformation due to continuous impact. To attach the bumper, a <sup>1</sup>/<sub>4</sub>-28 threaded rod was cut to 1 <sup>1</sup>/<sub>2</sub>" and a spacer made to allow the air cylinder a little more movement along the dovetail's stroke.

#### 2.3.7 Leveling Plate

The leveling plate was designed to allow for correction of any non-level surface the apparatus was placed on. An assembly is shown in Figure 2.12. The design consists of two plates, a large base plate with four threaded holes, and a smaller leveling plate with four threaded holes and four clearance holes. On the top plate was also mounted a bubble level. The four threaded holes in the top plate were for the height adjustment screws. These adjustment screws hold the top plate at a short distance above the lower plate. The clearance holes in the leveling plate were reserved for the four clamp screws that thread into the lower base plate. When tightened, these screws clamp down the top plate and hold it in place. Washers were used on the clamp screws to distribute the clamp pressure away from the edges of the clearance holes. A cross-sectional representation of this can be seen in Figure 2.13.

The bubble level on the top plate allowed for a fast, visual inspection of the alignment of the leveling plate. An evenly leveled plate was represented by the bubble being in alignment with a center ring in the bubble level.



Figure 2.12 Leveling plate assembly isometric view.



Figure 2.13 Leveling plate cross section depicting height adjustment screw and clamp screws with washers.

To adjust the level of the plate, loosen the four clamp screws holding the top plate to the bottom plate, and adjust the height adjustment screws until the bubble level indicates a properly level plate. Tighten the clamp screws incrementally around the plate to ensure the level is maintained while clamping the leveling plate to the base.

#### 2.3.8 Air Supply

The air supply for the cylinder comes from a filtered air source and is activated using a solenoid. The diagram of the schematic can be seen in Appendix C. Since these parts were donated, the system consists of readily available components found in many OEM manufacturing plants.

The air is introduced into a regulator/filter combination unit manufactured by SMC. The filter is to keep any contamination from entering the solenoid and air cylinder, and the pressure regulator allows for easy manipulation of the pressure delivered to the air cylinder. In the prototype, the air pressure controls the force acting against the plate. A gage is incorporated into the regulator to allow for easy determination of the current pressure setting.

From the regulator, the air enters the solenoid valve. This is a single acting, spring return solenoid valve manufactured by MacValves, Inc. It is operated by supplying 110VAC to the coil windings. Removing the supply voltage sends the solenoid back into its default configuration. This particular unit also has velocity controls on the output ports, to allow for control of the air velocity to the cylinder. Due of the tapping nature required for this project, the ports are currently left open as to leave the air velocity at its maximum.

From the solenoid, air goes directly into the air cylinder. With the solenoid at rest, the air cylinder's default position is retracted. Once the solenoid has been activated, air is sent into the rear port of the cylinder and the cylinder extends.



Figure 2.14 Assembly view of the air package. This was mounted to the right side wall.

# **2.3.9 Prototype Dimensions**

The overall dimensions of the machine are shown in Figure 2.15. The width and depth were approximately 12" in each direction. The height was approximately 13.5" tall.



**Figure 2.15** Overall machine dimensions shown with top, front, right, and isometric views.

## 2.3.10 Electronics

The last area that was designed was the electronics. The project was designed around an Arduino microcontroller. These microcontrollers are low cost, reliable, and highly documented, making them easy to integrate and program. The electrical schematic for the prototype system can be seen in Appendix D.

General functionality of the machine dictated that at least one push button be added for manual operation. A switch was chosen to allow for automated tapping, with a potentiometer added to control the tap frequency. Table 2.2 lists the functions and the microcontroller requirements for each one.

Function	Component	Туре
Single Tap	Push Button	Digital Input
Multiple Tap, Continuous	Switch	Digital Input
Cylinder Stroke Sensor	Limit Switch	Digital Input
Solenoid Activation	Relay	Digital Output
Timer for Tapping Interval	Potentiometer	Analog Input
Accelerometer Feedback	Accelerometer	Analog Input

**Table 2.2** Function List for Electronics Design

From Table 2.2, it was assumed that the project required three digital inputs, one digital output and two analog inputs on the microcontroller. The Arduino ATmega168 microcontroller mounted on a Duemilanove prototype board was chosen to fit these criteria. It runs on standard 3.3v-5v logic, and had more than enough inputs and outputs to fulfill the requirements. Other factors in this decision were the inexpensive cost of the board, ease of programming, and large community driven support groups. This made for fast development time of the prototype software.

Most of the inputs and outputs utilized a 5v power source. The Arduino provides this directly from the board. The only exception in the prototype was that the solenoid runs on 110VAC, which the Arduino cannot deliver. A 5v switching relay was placed in between the Arduino output and the solenoid. This allowed the Arduino to switch 110VAC without burning out the board. Pull down resistors were also added to the digital inputs. During construction and programming, it was determined that putting the single tap push button and the multiple tap switch in parallel would make the software to handle automated tapping much simpler.

For aesthetics, an enclosure was used to mount the boards and relay in. Holes were cut into the cover to place the button, the switch, and the potentiometer. Holes were cut into the side of the enclosure to fit power plugs, inputs, outputs, and the USB connection coming from the Arduino board.

The accelerometer was attached directly to the right side of the tap plate. The accelerometer chosen was an ADXL321 from Analog Devices. It is a three axis accelerometer with a +/- 18g range (Analog Devices, 2004). It was purchased from SparkFun with a convenient break-out board for ease of wiring. While only one axis is being measured on this application, the cost of the accelerometer was much less expensive than some single axis accelerometers. Only three wires needed to be used for the accelerometer: +5V, Gnd, and a single wire for the measuring axis. The other pins remained unconnected.

## 2.3.11 Software Development

The Arduino software is an open source package that is suitable for basic to mid level programming. It has some limitations, but for the prototype, these were never encountered. Programming the Arduino is very simple and straight forward. The code is a slightly modified version of C/C++ for embedded microcontrollers. To program the Arduino, a java-based programming interface has been developed. This uses a standard C compiler with libraries specifically built for the Arduino code set. This can be found on the Arduino's website (Arduino).

The source code for the Arduino can be found in Appendix E. The code was very simple and straight forward. The program initially set up the global variables and included libraries. A setup routine ran to allow the inputs and outputs to be defined, and the serial communication started. After this, the main program loop was entered.

The software looped continuously while polling the button/switch input. If it saw this input change to a high state it began executing a tap. It first set the timer value based on the analog voltage coming from the potentiometer. Then, it turned on the relay output, sending the cylinder up. The controller then jumped into a second loop, monitoring and reporting the state of the accelerometer and the current tap count. Once it saw the limit switch, it turned off the relay. It continued this loop until the timer event was reached, then jumped back up to the button polling loop to start again.

If the button was pushed once, the tap was initiated once. If the button was held down, or the switch was closed, then the tap repeated itself every time the main program loop reset. The results were sent back through the RS-232 connection established through the USB cable attached to the Arduino. This also provided the power for the Arduino. Data was returned in the form <CYCLE COUNT>,<ACCEL VALUE>. To store the data, a user needed to copy the data from a terminal window on the PC into a spreadsheet for analysis.

#### **2.4 Testing the Prototype**

After construction was completed, initial testing was required. In theory, all the design criteria established for the design had been achieved, but actual functionality was yet to be determined. Shortly into the testing phase, it became obvious that changes were needed.

The first series of taps did lift the floating plate into the air approximately 2 full inches. However, once at the top of the trajectory, the rails had a tendency to bind up and hold the plate in position. It was determined the IGUS tracks, along with some errors in

the manufacturing process were creating an uneven alignment between the four vertical tracks, and causing the bind.

After adjusting the plate and rails, and adding some lubrication to the slides, a workable test was able to be performed. This was used to determine the validity of the accelerometer feedback. Figure 2.16 shows the graph of one of the sample tap profiles.



**Figure 2.16** Accelerometer feedback profile from tap 6 of 19. The X-axis represents the actual, normalized feedback from the accelerometer. The Y-axis is the sample number taken during the tap test.

In order to properly determine how accurate this graph is, it was necessary to determine what the theoretical acceleration profile must be. Figure 2.17 shows the graph of the expected motion. The initial impact on the plate causes a sudden, instantaneous acceleration. Once the impulse has ended, the plate immediately starts to decelerate at the rate of gravity, while rising along the vertical axis. At its apex of motion, the plate velocity reaches zero, and the plate accelerates at the same gravitational rate until it meets

the hard stop, at which point a sudden, instant deceleration is achieved, bringing the plate to rest. The rapid acceleration of the end of motion is expected to be higher than the initial acceleration due to the fact that the plate has to fall a distance of  $S_B+S_C$ .



Figure 2.17 Theoretical acceleration profile for motion of tapped plate over time.

A comparison of Figures 2.16 and 2.17 indicates that the accelerometer was functioning correctly, but limitations in the hardware were causing sometimes erratic, results. By using the x-axis sample rate in Figure 2.16 as a pseudo-time function, it did become clear where the different acceleration/deceleration zones originated and ended. Sample readings 10-12 are the initial impact zone shown in Figure 2.17. Samples 12-40 are the deceleration due to gravity and friction of the rising and falling plate. Samples 41-43 show the acceleration of the plate as it reaches the hard stop.

Frictional and alignment inaccuracies can be seen in the shortened motion of the falling plate as opposed to the rising plate. The impact of the hard stop is also dampened significantly in the sample test when compared to the theoretical value. This can be explained by observing the motion as the plate hits the hard stop. Instead of an immediate halt to motion, the plate actually bounced at the bottom of motion, resulting in the seemingly erratic acceleration at the end of the sample test.

While the individual zones can be determined, the actual motion of the plate is very different than the theoretical motion. This was attributed to problems with manufactured parts, as well as the loose tolerances of the rails. Friction also played a considerable roll in the plate acceleration through the stroke.

The second measurement device on the prototype was a scale mounted to the slide of the left, forward rail mount. During testing, it was determined this would be inadequate for continued operation as it would require some sort of high-speed camera and subsequent analysis to be able to properly determine the apex of motion.

## **CHAPTER 3**

## **PROTOTYPE DESIGN REVISIONS**

## **3.1 Prototype Design Changes**

Once the prototype was tested, problems were immediately discovered.

- The rails were not smooth and rigid enough to provide a consistent motion to the sample container.
- When the rails did eventually work, the downward force of the plate on the stop pins caused the entire plate to bounce instead of stopping when intended.
- The height verification scale was determined to be ineffective without additional costly equipment.
- The accelerometer feedback was not scaled so that a calibration to deliver actual accelerations was needed. This task would also be difficult without incorporating some sophisticated devices and the post-processing of captured data.
- Operation of the controller required a computer. This placed a constraint on the ease of use of the prototype.
- Feedback data was sample based, and not based on real time, making subsequent calculations difficult.
- Mining the data proved to be especially cumbersome. Some sort of automatic storage would have been much more convenient.

These issues provided the stage for the revision of the prototype.

#### 3.1.1 Rail Analysis

The vertical rails were the most disappointing aspect to the prototype functionality. Between the mounts and the rails themselves, binding issues wreaked havoc on the performance of the device. To make matters worse, the tapping plate as designed was excessively bulky and awkward. When the tapping plate did eventually fall, the pins were so thin and flexible, that it caused the plate to bounce. This created inconsistent acceleration readings at the end of the stroke.

It was determined that the rails and tap plate would need to be scrapped and a new solution found in order to provide a more efficient, lower friction test environment. A new end stop would also need to be found. The bouncing motion was determined to be suboptimal, and would need to be corrected for the next revision.

Eliminating the current rail design also meant that the side walls would need to be redesigned to fit whatever new solution was chosen. This also meant that the cylinder mount would need to be redesigned based on the fact that the rear wall took its support from the side walls, and the dovetail was only really needed if the next rail design had a fixed end stop.

## 3.1.2 Feedback Device

The height verification scale and accelerometer were used to try and obtain motion data from the prototype tests. During testing, it was determined these were wholly inadequate. While the accelerometer did return valid results, they were not scaled properly and did not correspond to real world values. The height scale relied on obtaining a high speed camera, which is both expensive and cumbersome. Data from the camera would need to be matched with each tap, and there would still be no effective, reliable way to match the incoming sample data to a specific frame on the camera.

To this end, it was decided that a better solution may be direct distance feedback right into the controller itself. The controller could then be used to match a distance measurement along with a timestamp on every sample taken. Many forms of distance measurement devices are readily available and some for very low costs. By interfacing a distance measurement device directly into the controller and time stamping each reading taken, it was also decided that the accelerometer was more redundant than necessary and could be eliminated from the revision.

## **3.1.3 Electronics Revisions**

The electronics designed for the prototype functioned as intended, but testing proved that the intention of the design was flawed. Constraining the machine to be used with a computer added more expense to the project than was necessary. Carrying a computer around with the device also creates unnecessary work. The Arduino chosen for the prototype was determined to be quite effective, so that was kept, and solutions to the electronics shortcomings were researched.

The first addition to the electronics decided upon was some sort of removable storage device. This could be in the form of a flash drive, or USB thumb drive. Using a removable storage device meant that the machine no longer required a computer for testing, just data analysis. The machine could be set up anywhere, tests could be run, and then when the user was finished, the memory removed and the data analyzed at a later date. The only downside to this is that the power for the microcontroller was previously delivered through the USB connection to the PC. This meant another power source was required to run the electronics.

The simple button-switch-potentiometer design for the prototype worked well. However, it did not allow for many options or configurations without a PC being available for direct program changes. It was decided that an LCD may be a valuable UI alternative to the simple interface. A few buttons for menu navigation and selection would be all the inputs required for the user, and the test parameters could be altered directly at the device, without having to connect a computer.

## 3.2 Revision Implementation

#### 3.2.1 Alternative Rail Assembly

The most major required change to the function of the prototype was to fix the rail assembly in order to avoid the friction and binding issues associated with the IGUS linear bearings used in the first design. In many applications, the IGUS bearings provide a smooth, low-friction motion and work very well. The major problem in this application was a lose fit between the carriage and the aluminum track, combined with machining inaccuracies with the plate mount. In this instance, the mounts were determined to have been machined at an acute angle, not perpendicular. When these were bolted to the IGUS carriages, the loose fit provided enough room for the carriage to twist in the track and cause binding issues between the four rail assemblies.

The solution chosen for the revision was a linear ball-bearing design. Ball bearings provide a low-friction environment along with high torsionnal rigidity in all constrained directions. Standard industrial linear bearings come in a variety of shapes and sizes. The primary configurations are a rectangular, non-rotating track and carriage combination or a round, linear bearing that rides on a cylindrical shaft.

In this design, it was determined that with the structural rigidity of linear bearings, two assemblies would be sufficient to hold the plate into position. Adding more bearing assemblies increases the rigidity, but at the expense of added friction and possible conflicts with inaccurate machining processes, as seen in the prototype. A single, non rotating track and carriage assembly was considered. This would provide the lowest friction and could be fitted to the current walls, but these can be expensive and cumbersome when designing it to lift cantilevered weights in a vertical direction. Since it was also proven that there were manufacturing problems with the current plate mounts and plate, these would have to be redone anyway.

In the end, twin round linear bearings were chosen. These bearings travel along a hardened steel shaft. After researching different round bearing confirmations, a flanged, 3/8" linear system was chosen. The flange eliminates the mounts required to adapt the lifting plate to the linear bearing. Simple clamps can hold the lower end of the vertical steel shaft, allowing for some minor deflection in the rails to accommodate for misalignments in the center distances between the bearings and the shafts.

The linear bearings were purchased from *VXB.com*, an internet retailer that specializes in distributing linear bearing systems. Also purchased from VXB was a long piece of case-hardened 3/8" steel rod. This is polished and hardened to a Rockwell hardness of 60-64 Rc. This provides a solid, smooth interface for the ball bearings to travel along. This rod is also precision ground to a diameter of .3745", meaning that



diameter interference along the length of the shaft is kept to a minimum (VXB Ball Bearings, 2010).

Figure 3.1 Exploded view of the revised rail assembly design.

## 3.2.2 End Stop Dampening

The end of travel of the plate on the prototype was dictated by four pins at the end of the IGUS rails. Problems were discovered with this setup in the testing stage. When the

plate reached the bottom of freefall, the mounts would bounce when contacting the pins. This created an under-damped situation in the motion profile. When studying the effects of a tapping motion on granular particles, an under-damped vibration at the end of the motion profile can add undesirable results to the tapped density test.

To fix the bouncing issue, a shock absorber was designed into the system. In order to choose the correct shock absorber, some calculations were needed. A major supplier of shock absorbers is the company SMC Corporation. Calculations for shock absorber selection can be found directly in their product selection manual.

The first necessary calculation is the velocity of impact. Equation 3.1 is the calculation for this velocity.

$$v = \sqrt{2gh} \tag{3.1}$$

In this equation, g is the gravitational acceleration in meters per second squared. The variable h is the freefall height of the plate and cylinder. The second series of calculations are required to determine the damped energy in the system.

$$E_1 = mgh \tag{3.2}$$

$$E_2 = mgS \tag{3.3}$$

$$E = E_1 + E_2 (3.4)$$

Variable m is the mass in kilograms of the falling object. S is the damping distance at the end of travel. The last calculation needed is the corresponding weight of the impact object, denoted as Me.

$$Me = \frac{2}{\nu^2}E\tag{3.5}$$

Preliminary values were entered in order to determine the proper shock absorber for the new tap plate. According to the initial design requirements, the system must be able to handle 1.125" of travel. Preliminary measurements on the tapping plate show that the approximate weight without a sample on top is 500 grams, or .5 kg. For a factor of safety in these calculations, the height and weight used in the preliminary calculations were 2" and 1kg, respectively. The results need to be in metric units, so 2" translates into .0508m. The acceleration of gravity is a constant 9.8 m/s<sup>2</sup>. Substitution of these values into Equations 3.1, 3.2, 3.3, and 3.5 yields the following table.

.498 Joules .0508 m E1 h 1 kg E2 .059 Joules m  $9.8 \text{ m/s}^2$ E .557 Joules g .998 m/s Me 1.118 kg v

 Table 3.1 Initial Conditions for Shock Absorber Selection

These values were then used to choose the correct shock absorber by utilizing the table provided in the selection manual from SMC. By using the chart given in Figure 3.2, the RB0805 was found to be able to sufficiently dampen the plate and sample. However, the

weights and heights used in the initial conditions were not exact, so an RBC0806S was chosen in order to provide a sufficient factor of safety to the calculations. Note that the C in the part number denotes a plastic cap on the shock absorber, and the S denotes a stop nut so the shock absorber does not bottom out in range of motion. In the end, the stop nut was not required.



**Figure 3.2** Selection chart provided by SMC for the easy selection of shock absorbers using the calculations provided. **Source:** (SMC Corporation, 2006)



Figure 3.3 Shock absorber mount assembly.

# 3.2.3 Height Verification

The next stage of the prototype revision was to determine a better alternative to a visual scale for determining the apex of motion during the tests. The most obvious solution to this problem was to provide sensory feedback to the controller during the motion in order to directly measure the distance traveled. If the exact position of the slide can be determined and matched to a time interval, then the velocity and acceleration at any given time can also be easily calculated.

Solutions for position measurement range in both form and function. In this instance, the simplest solution was to attach an encoder to the table in such a way as to measure the vertical movement.

A sensor from Avago Technologies was chosen to fulfill this task. The sensor is an AEDS-9641-P10. This is a 2-channel, 150 line per inch optical encoder. The internal diagram is shown in Figure 4.2. The functioning pulse train can be seen in Figure 4.3.



AEDS-964x Series Block Diagram

**Figure 3.4** Block diagram of the AEDS-9641-P10. The left hand side depicts the Emitter. The right hand block shows the dual channel detectors. **Source:** (Avago Technologies, 2010)
#### **Output Waveform**



**Figure 3.5** Pulse output of dual channel detectors. **Source:** (Avago Technologies, 2010)

By utilizing the optical encoder and a 150 lpi codestrip, it was possible to create a vertical encoder that measured the distance traveled. Using this encoder values it should be possible to also calculate the velocity and accelerations of the sample during the entire range of motion.

#### 3.2.4 Electrical and Software Design Changes

Additions to the electronics portion of the project included a microSD card reader, an LCD, a prototyping board, and the new optical encoder. Removed from the new design was the accelerometer, potentiometer, and manual tap switch. The potentiometer and

manual tap switch were no longer needed with the new functional setup, and the accelerometer was omitted on the second design for a number of reasons. The time to properly implement both the accelerometer and the encoder was prohibitive. It was also unnecessary. With the encoder properly functioning, all velocities and accelerations can easily be calculated through the entire motion, so there is no need to measure it directly. Due to a lack of instrumentation, proper calibration of the accelerometer would have been difficult.

The LCD is a 2-row, 16-column display. The product chosen was a SerLCD from SparkFun Electronics. Communication with the LCD is achieved through an RS-232 backpack mounted on the rear of the display. The TX pin on the Arduino controller is wired to the RX pin on the LCD, and commands are sent using special control signals. (SparkFun Electronics, 2006)

The microSD shield is a pre-built unit that is designed by SparkFun Electronics to fit directly on top of the Arduino main board. This makes interfacing with the reader very simple as no special wiring needs to be implemented. The only difficulty in implementing this was to be able to read and write to the card in a format that a standard computer can read. The SdFat library was used in order to simplify reading and writing to the card. This allows the program to use simple commands in order to write text files to the flash card. Due to limitations with this library and the Arduino itself, it is not currently possible to write actual spreadsheet files to the card, but it is relatively simple to implement a comma-separated text file which can be imported into a spreadsheet for data analysis.

A prototyping board was added next. Like the microSD shield, the prototyping board was designed by SparkFun specifically to interface with the Arduino main board. This provided a top layer interface for buttons, LEDs, and other components. In this case, the board was used to mount three pushbuttons for navigation of the LCD menus. Two built in LEDs were also utilized in order to provide information to the user. The first LED is lit whenever power is applied to the Arduino, and the second is lit whenever a test is in progress.

As previously discussed, the optical encoder was installed and had to be programmed into the software. This proved to be one of the more difficult aspects of the second design, not because of any wiring issues, but of some bad code used as reference material. The Arduino provides two inputs that can be utilized as interrupt inputs. These are scanned on a regular basis by the controller and as such, provide a much faster response time than the normal inputs. They can automatically trigger events in the controller based on their state without harming execution of the rest of the software. The Arduino website provided numerous examples of different ways to program quadrature encoder inputs in the software using these interrupts. Problems arose when some of the sample sketches were found to provide false feedback and erratic encoder readings. One of the sample sketches did prove to be the solution, however.

Once the new components were determined, wiring of the new system was completed. The electrical schematic is shown in Appendix D. When doing the wiring for the prototype revision, a few other improvements were also made in the way the inputs and outputs were laid out and interfaced. The first change was the removal of a pull down resistor for the input buttons. In the first prototype, a 10k ohm resistor was used to pull the input down to ground. Upon further research into the Arduino's capabilities, it was discovered that the controller has built in pull-up resistors for all inputs. This means that the only pull down resistor needed was for the limit input, as this is a requirement for the limit itself. The encoder inputs require that no pull-up or pull-down resistors be used, as specified in the manual (Avago Technologies, 2010).

Another change to the system was that manual input switches were moved to the analog input lines. These lines can function as both analog and digital inputs, so in order to conserve space on the limited digital inputs and outputs, the analog inputs lines were used instead. Since only three buttons were wired in, this leaves the possibility of two additional analog sensors, should the need arise.

#### **3.3 Final Assembly**

The final assembly is shown in Figure 3.5. Overall, this was a much more efficient design in terms of size and manufacturing labor. The components were much easier to produce, required less material to make, and there were a fewer number of components overall. This design did require a bit more design and calculations than the prototype, however. In the end, the longer development time produced a much cleaner, nicer machine.

Figure 3.6 displays the overall dimensions of the new device. The footprint remains the same, as the leveling plate and base were both carried over from the first design, but the height and weight have been reduced thanks to smaller, lighter components.



Figure 3.6 Final assembly of revised prototype.



Figure 3.7 Overall dimensions of prototype revision.

### **CHAPTER 4**

### CONCLUSIONS

## 4.1 Testing the Revised Device

After the revisions were made to the prototype, the device was tested to determine the effectiveness of the changes. During testing, additional bugs were removed from the software. Overall, the revised device functioned much more reliably and accurately than the prototype. Data obtained from the prototype was very positive.

TAP0001.TXT	- Notepad	
File Edit For	mat View Help	
TAP0001.TXT Pitch (ms): Sample.Time 1,0,0 2,9,3 3,19,3 4,30,13 5,40,150 6,50,377 7,59,638 8,70,907	501 (ms),Encoder (in*1000)	*
9,80,1178 10,90,1407 11,99,1611 12,109,1768 13,120,1887 14,130,1965 15,140,2007 16,149,2009 17,160,1970 18,170,1897 19,180,1783 20,189,1629 21,200,1442		
22,210,1217 23,220,957 24,230,660 25,240,325 26,250,56 27,260,83 28,270,138 29,279,98 31,300,86 32,310,71 33,320,58		
34, 330, 50 35, 340, 48 36, 350, 51 37, 360, 50 38, 370, 45 39, 380, 50 40, 390, 48 41, 400, 46 42, 411, 48 43, 420, 48		
45,440,46 46,450,46 47,460,46 48,470,46 49,480,46 50,490,46		Ţ

Figure 4.1 Sample test results displayed in the raw text file.

Figure 4.1 is a screenshot taken of the actual test data stored on the microSD card. This is a full tap reading. The data was imported into Microsoft Excel for analysis. After it was scaled, the displacements were used to calculate the velocity and acceleration profiles. These are shown in Figures 4.2, 4.3 and 4.4.



Figure 4.2 Distance profile of results from TAP0001.txt.



Figure 4.3 Calculated velocity profile of results from TAP0001.txt.



Figure 4.4 Calculated acceleration profile of results from TAP0001.txt.

The acceleration profile for the test profile is much closer to the theoretical acceleration profile expected for the motion. The large acceleration at the end of the move is the fall from  $S_B+S_C$ , and the damping at the end of the profile can be seen in a greatly reduced error in the distance profile.

To determine repeatability of tap tests, these results were graphed with another random sample test using the same settings. The results are displayed below.



Figure 4.5 Distance profile for TAP0001 and TAP0011.



Figure 4.6 Velocity profile for TAP0001 and TAP0011.



Figure 4.7 Acceleration profile for TAP0001 and TAP0011.

The results are similar. Not only was the revised design functioning correctly, but the results were repeatable as well. In the velocity profile, an anomaly did reveal itself. During the transition from heavy acceleration to deceleration, the velocity profile shows a slight wave at the peak velocity. This was more than likely caused by the bearings used in the device. While these bearing were infinitely better than the IGUS rails originally designed in, they were still not a perfectly smooth motion. There was a slight cogging effect to the motion of the ball bearings. This can be fixed with a better grade of ball bearing.

#### 4.2 Design Criteria Results

The data retrieved from the device was beneficial in determining the profile of the tap. However, to truly tell if the design was adequate, it needed to be compared to the original design criteria that it was supposed to meet. The stroke of the cylinder, along with the force provided by the air pressure, meets or exceeds the design specifications. The impact zone can be altered in any way the user sees fit, and the pressure is directly correlated to the force delivered. In testing, it was determined that the 1.125" stroke capability is adequately reached. In the test results provided in this thesis, the sample cylinder reached a height of approximately 2".

The linear rails provided an excellent, stable motion and maintained the vertical motion of the sample container. They also supported the largest 3" sample container size without any issues. The encoder feedback also adequately captured the motion profile. The last mechanical addition, the shock absorber, functioned well in dissipating the force of the falling sample container. There was still a marginal bounce, but overall, the impact was greatly reduced.

Electronically, the design provided a clean, simple user interface. Problems that arose during testing were believed to be the result of some loose wiring in the system. Problems manufacturing the electronics enclosure resulted in loose connections between the circuit boards that seem to interfere with the LCD on occasion. These problems are small and easily regulated for testing purposes, but will have to be resolved if the device ever intends to reach a production environment.

Overall, the device functions remarkably well in dealing with all of the original and revised design criteria. Future testing will be needed for durability and sustainability, but current test indicate a successful build.

#### 4.3 Future Revisions

In the end, like any design, changes are always possible. No design is without its limitations or faults. During the process of designing and building the revised device, many options became apparent for added features and improvements. These were not implemented because of constraints in time, material, and funding. Many of these improvements may have been implemented, but required a fundamental design change after significant time and energy investments were already spent.

### 4.1.1 Smaller Device Footprint

The overall dimensions of the device shrunk considerably on completion of revision A. This was due in large part to the removal of out walls, corner posts, and the dovetail assembly, as well as the redesign of the tapping platform. Still, the overall footprint of the machine remains the same. This could be reduced significantly. The size of the base was chosen to provide a stable foundation and sufficient weight for the test apparatus during the prototype design. With a smaller momentum of the tap plate, and alternate materials for the base, this could be reduced to the size of the leveling plate or less.

#### 4.1.2 Larger Sample Sizes

As proven by the calculations in the prototype design phase, the air cylinder provides sufficient force to move the range of samples through the desired stroke. In the future, a new tapping plate could be constructed that allowed for sample containers greater than 3" in diameter.

#### 4.1.3 Force and Acceleration Sensors

Additional sensors could also be beneficial to the test apparatus. A force sensor attached to the end of the cylinder bumper could provide direct, actual force feedback to the system, allowing the force to be data logged alongside the position and time.

The original prototype had an accelerometer, but with the new design, and limited time and resources, it was determined to be redundant and not completely necessary. Due to this, the accelerometer was taken off. Future revisions could incorporate the accelerometer back into the system in order to verify and prove motion calculations.

#### 4.1.4 Ball Bearings

The ball bearings used in this system were 3/8" flanged bearings. They are an industrial standard design which means that many companies produce similar types of bearings. The difference in bearing manufacturers generally lies with the quality of the balls and raceways in the bearings. The NB bearings from VXB worked for the design, but were found to be a bit stiff and motion had a cog effect to it. Replacement of these bearings would be a very simple, marginally inexpensive upgrade to this project.

#### 4.1.5 Improved Software and Controls

The Arduino is a very versatile microcontroller, but it does have its limitations. In the end, a better revision might be a new controller all together. However, with some clever programming and electronics, it may also be possible to enhance the functionality of the Arduino.

Most of the actual design work on this project focused on the mechanical design of the device, itself. Another beneficial future upgrade would be to the electronics package. Taking the time to design and build a sturdy user controls box would give the device a better, more complete polish.

Updating the Arduino itself might be an upgrade to explore. The Arduino has many different shapes and sizes, and smaller boards are being developed every day. A smaller, more mobile microSD card reader, and a smaller Arduino main board would make the final control panel a lot more compact and less cumbersome.

The LCD currently uses the dedicated RS-232 communications line running from the Arduino. This same RS-232 channel is also used in the USB interface to communicate with the PC. Currently, the system is designed to only work independently of a computer. Changes to the inputs and software could allow the controller to run off a computer or the memory card, giving the user more choice and flexibility.

Programming alone could improve the device immensely. The encoder output and the SdFat library in the arduino currently are set to only work with integer values. This means that all the position data must be scaled by the user at analysis time. Figuring out how to write decimal data to the microSD files would greatly enhance the data collection.

The last two improvements that could be made to the code have to do with memory allocation and management. During the programming, errors kept cropping up during the software testing. With some extensive troubleshooting, it was finally determined that the program was running out of memory during operation. The program size, along with all the globally defined variables were overloading the memory and causing erratic behavior. Many tricks were used to try and free up space, and eventually, it worked again, however, there is room for much more improvement. Due to limited memory resources and some less than optimal coding, the number of samples taken during a tap had to be limited. If more efficient code were written, this could be increased to allow for a shorter time interval with more data points per tap. On this same note, if more sensors needed to be added, more efficient code would also be needed to allow for storage of more data during run time.

The last option to upgrade the device would be to use an alternate controller. Floating point values in the encoder position feedback would provide a much cleaner data logging system. Faster port polling speeds would ensure that no encoder values are lost. The limit switch would be better off as an interrupt, but the Arduino's only two interrupts were utilized for the more important encoder feedback.

## **APPENDIX A**

## ASSEMBLY DRAWINGS

The figures contained in Appendix A detail the assembly views of the prototype and the revised tap apparatus. They display exploded views of the components of each system in such a way as to allow for easy assembly and disassembly of the components. Balloons reference the itemized parts lists at the end of each set of figures.



A.1 Prototype Assembly Drawing

**Figure A.1** Assembly view of left wall. Screws are fastened in place, while the pins are press-fit into their respective holes.



**Figure A.2** Assembly view of right side wall. Again, screws are fastened into place, while pins are a press-fit. Note the position of the air pack mounting holes when assembling.



**Figure A.3** Assembly view of left and right walls with rear wall and leveling plate. The rear wall attaches directly to the two walls, with a clearance hole at the bottom for air and sensor lines.



Figure A.4 Assembly drawing detailing the dovetail and cylinder mount assembly.



Figure A.5 View showing the assembly of the rails and plate mounts.



Figure A.6 Assembly view of the tapping plate.



Figure A.7 View of the assembly of the machine to the base plate.



Figure A.8 Assembly of air pack, level, and height scale.



Figure A.9 Assembly view of lexan guards.

	_			<u>6</u>						1		
- I							PARTS	S LIST	ſ			
1	ITEM	QTY	PART	NUMBER					DESCRIPTION			
	1	1	0001		Plate, Leve	eling						
	2	1	0002		Wal <b>l,</b> Left	Side						
	3	1	0003		Wall, Righ	t Side						
	4	1	0004		Upright, Fi	ront Le	ft					
	5	1	0005		Upright, B	ack Le	ft					
- [	б	1	0006		Upright, B	ack Riç	jht					
	7	1	0007		Upright, Fi	ront Ri	ght					
	8	4	0008		Bracket, A	ngle						
В	9	1	0009		Plate, Mov	/ing						в
10 1 0010 Mount, Dovetail												
	11	1	0011		Dovetail, F	emale						
- [	12	1	0012		Dovetail, N	Male						]
- [	13	1	0013		Mount, Cy	linder						1
[	14	1	0014		Spacer, Cy	linder						1
	15	1	0015		Bumper							1
- [	16	2	0016		Cover, Sho	ort						1
	17	1	0017		Cover, Rea	ar						1
	18	1	0018		Cover, Lor	ng						1
	19	1	0019		Scale							1
	20	1	0020		Pointer							1
₽	21	1	0021		Plate, Clar	np						H
	22	1	0022		Clamp, Ca	rtridge						1
- [	23	1	0023		Mount, Ac	celeror	neter					
	24	4	0100		1/4-20 x 1	-1/4 S	HCS, ALL	.0Y				
- [	25	4	0101		1/4-20 x 1	BRAS	S TIP SE	t scr	EW, ALLOY			
	26	4	0102		WASHER,	1/4" H	EAVY					
	27	8	0103		1/8 x 1 D0	OWEL R	PIN					
	28	8	0104		#4 WASH	ER, SS						
- [	29	4	0105		WASHER,	#10 H	EAVY (3/	/16)				
	30	2	0106		10-32×3/8	SHCS,	ALLOY					
- [	31	25	0107		10-32x1/2	SHCS,	ALLOY					
1												
А	DRAW! De lor	v va la	shua	5/4	/2010							A
- 1	CHECK	ED			92010							
						TITLE						1
	Q,A,											
-						Tan						
- 1	Tapping Apparatus											
	APPRO/	VED										
						\$1ZE			DWG NO		REV	1
						Δ			Tanning Asse	mhly		
						SCALE			apping Asse			-
l										SHEET 10 OF 11		1

**Figure A.10** First half of the parts list for the prototype assembly.

			2	<b>↓</b> 1										
PARTS LIST														
	ITEM	QΤΥ	PART NUMBER	DESCRIPTION										
	32	8	0108	10-32x1-1/4 SHCS, SS										
	33	1	0109	VALVE, MAC 4-WAY, 1/8" NPTF, SINGLE-OPERATOR, SPRING RETURN	1									
	34	1	0110	Nipple, 0.125 NPT x 1.500	1									
	35	1	0111	BRACKET, FILTER/REGULATOR, SMC UNIT	1									
	36	2	0112	M35 x 8mm SHCS, ALLOY										
	37	6	0113	M35 x 6mm SHCS, ALLOY	4									
	38	1	0114	LEVEL, SURFACE MNT CROSS-HAIR	4									
	39	4	0115	IGUS TRACK										
в	40	2	0116	Fitting, Quick Release, 0.25 ID, 10-32 thd	в									
	41	1	0117	BREATHER VENT, 1/8" NPT	AIREK VENT, 1/6" NPT									
	42	4	0118	REW, #10-32x1-3/4 SOC HD CAP, SST										
	43	3	0119	SCR, 4-40 X 3/8 RND HD SST	4									
	44	8	0120	5-40 x 0.250 FLT HD SLT, SS	-									
	45	16	0121	8-32 x 1/4 RND HD, PHILLIPS, SS	-									
	40	1	0122	FILTER REGULATOR ONLY (SMC)	4									
	47	1	0123	CYLINDER, BIMBA, 3/4" STROKE	-									
	48	2	0124	Hitting, Quick Release, 0.25 ID, 0.125 NP1	-									
	49	1	0125	/4-28 x 1.5 Threaded Rod										
	20	1	0126	WACHED AS COLLAT	-									
-	57	1	0127	9.3745/9 CHIC CC										
۲	32	1	0120	o sexs/o sinca, as	L.									
4	DRAWI	u Ing. Je	nshua 5	4/2010	A									
	CHECK	ED	osnua o,	4/2010										
				TITLE	-									
	QA													
	MFG			Tapping Apparatus										
	APPRO	VED												
				SIZE DWG NO REV	1									
				A Tapping Assembly										
				SCALE SHEET 11 OF 11										
			2	<b>4</b> 1	_									

Figure A.11 Second half of parts list for the prototype assembly.

# A.2 Revision Assembly Drawing



Figure A.12 Top tapping platform assembly.



Figure A.13 Rail and cylinder assembly.



Figure A.14 Shock absorber, encoder, and top plate assembled onto rails.



Figure A.15 Leveling plate assembly detail.



**Figure A.16** Assembly drawing showing the leveling plate being attached to the base plate.



Figure A.17 Air package assembly diagram.

	PARTS LIST											
ITEM	TEM QTY PART NUMBER DESCRIPTION											
1	1	0001	PLATE, LE	PLATE, LEVELING								
2	1	0015	BUMPER	BUMPER								
3	1	0021	PLATE, CI	AMP								
4	2	0025	CLAMP	LAMP								
5	1	0026	ADAPTER	PLATE								
6	1	0027	PLATE									
7	2	0028	SHAFT									
8	1	0030	END STO	ND STOP CLAMP								
9	1	0031	CLAMP PL	LAMP PLATE								
10	1	0032	MOUNT, /	OUNT, AIR PACK								
11	1	0033	MOUNT, F	ENCOD	ER							
12	1	0034	Nipple, 0.	125 NP	T x 1.50	0						
13	2	0035	CLAMP, O	ODEST	RIP							
14	2	0036	MOUNT, (	CODEST	TRIP							
15	1	0037	SPACER									
17	4	0100	1/4-20 x 1	1-1/4 S	HCS, ALI	LOY						
18	4	0101	1/4-20 x 1	1 BRAS	S TIP SE	T SCF	REW, ALLOY					
19	4	0102	WASHER,	1/4" H	EAVY							
20	2	0105	WASHER,	WASHER, #10 HEAVY (3/16)								
21	6	0107	10-32x1/2	2 SHCS,	ALLOY							
22	1	0109	VALVE, M	VALVE, MAC 4-WAY, 1/8" NPTF, SINGLE-OPERATOR, SPRING RETURN								
23	1	0111	BRACKET	, FILTE	R/REGUI	ATOP	R, SMC UNIT					
24	1	0114	LEVEL, SU	JRFACE	MNT CF	2055-	HAIR					
25	2	0116	Fitting, Q	uick Re	ease, 0.	25 ID	, 10-32 thd					
26	1	0117	BREATHE	R VENT	, 1/8" N	РТ						
27	3	0119	4-40 X 3/	8 RND	HD SST							
28	1	0122	FILTER R	EGULAT	FOR ONL	Y (SN	1C)					
29	1	0123	CYLINDER	R, BIMB	IA, 3/4" !	STRO	KE					
30	3	0124	Fitting, Q	uick Re	ease, 0.	25 ID	, 0.125 NPT					
31	10	0128	8-32×5/8	SHCS,	SS							
32	1	0130	1/4-28 x 1	1 Threa	ded Rod	1						
DRAW		schurz	11/28/2010									
CHECK	ED ED	Ishua	11/28/2010									
See 1 Harrison 11	20			TITLE								
QA				TITLE								
MFG	MFG			TAPPING APPARATUS								
APPRO	MED											
	122			\$17E			DWG NO		DEV			
				Δ			Tanning Acco	mbly	PLL I			
				A			Tapping Asse	mbiy				
				SCALE				SHEET 7 OF 8				

Figure A.18 First half of the parts list for the revised prototype.

PARTS LIST													
ITEM	OTY	PART NUMB	ER				DESCRIPTION						
33	2	0131	1/4-20 x 1	L SHCS,	ALLOY								
34	8	0132	10-32 x 3	/4 SHC	S. ALLOY	(							
35	6	0133	8-32 x 3/4	-32 x 3/4 SHCS, SS									
36	2	0134	LINEAR B	NEAR BEARING									
37	1	0135	CODESTR	IP									
38	1	0136	SHOCK A	SORB	R								
39	1	0137	SENSÖR,	<b>OPTICA</b>	UL								
40	4	0138	10-32 x 2	SHCS,	SS								
41	4	0139	10-32 x 5	/8 SHC	S, ALLOY	ſ							
42	8	0140	RUBBER F	T00									
DRAWI De lor	v va le	orbura	0100/00/0										
CHECK	ED	JSHUM	11/20/2010	1									
				TITLE									
QA				1									
MFG				ΤΑΡΙ	PING	APP	ARATUS						
APPRO	VED			1									
				\$1ZE			DWG NO		REV				
				Α			Tapping Asse	mbly					
				SCALE				SHEET 8 OF 8					

Figure A.19 Second half of the parts list for the revised prototype.

## **APPENDIX B**

## PART DRAWINGS

This appendix contains the drawings that were used to create the initial prototype. To fit these drawings into the appendix the scale has been change. These prints are not to scale.


**Figure B.1** Drawing 0001 shows a 2-view drawing of the leveling plate used in the base of the machine.



**Figure B.2** Drawing 0002. 3-view drawing of the left hand side wall used to support the rail mounts.



Figure B.3 Drawing 0003. A 3-view drawing depicting the right hand side wall.



Figure B.4 Drawing 0004. A 2-view drawing of the front left upright with cutout for height scale.



Figure B.5 Drawing 0005 depicts the rear, left hand upright for the rail mounts.



Figure B.6 Drawing 0006 depicts the rear, right hand upright for the rail mounts.



Figure B.7 Drawing 0007. 2-view drawing of the front, right hand upright.



**Figure B.8** Drawing 0008 shows a 3-view drawing of the tapping plate mounts. The manufacturing of these were determined to be one of the causes of failure of the prototype. The angle of the material used was found to be slightly more acute than  $90^{\circ}$ , causing misalignment in the rails.



**Figure B.9** Drawing 0009. The tapping plate ended up being a bit thicker than necessary. The next plate was made thinner to save on weight.



Figure B.10 Drawing 0010 shows the rear mounting plate for the dovetail block.



**Figure B.11** The dovetail block is shown in Drawing 0011. This creates a vertical adjustment and locking mechanism for the air cylinder.



Figure B.12 The mating dovetail section is shown in drawing 0012.



**Figure B.13** Drawing 0013 describes the mount for the cylinder. This is attached to the dovetail



**Figure B.14** Drawing 0014 is the 2-view drawing of the cylinder spacer. This is part of the adapter to attach the bumper.



**Figure B.15** The bumper is described in the 2-views of drawing 0015. This is one of the few parts made from a material other than aluminum, and is also one of the few machined parts carried over to the revision.



**Figure B.16** Drawing 0016 shows the 2-view drawing of the first of three lexan cover plates designed for the prototype. These were never completed as the design was revised before these were required.



Figure B.17 Drawing 0017 shows the rear lexan cover.



**Figure B.18** Drawing 0018 depicts the front lexan cover. This was the full length of the tap apparatus to allow for maximum viewing during experimentation.



**Figure B.19** The linear height scale is shown in drawing 0019. Manufacturing difficulties made this impractical to manufacture, so an alternate scale was used.



**Figure B.20** Drawing 0020 is a 3-view drawing of a height pointer. This aligned with the scale to allow for manual reading of the height of the tap.



**Figure B.21** This is the main base plate. This was used on the first prototype, but revised to include the two countersunk holes from the rear side for the second design.



**Figure B.22** The cartridge clamp in drawing 0022 was designed to hold the sample cylinder onto the tapping plate.



**Figure B.23** A small mounting plate was designed as shown in drawing 0023. The accelerometer was glued onto this plate for acceleration feedback.



**Figure B.24** This was the first part designed for the revision of the prototype. It is the mounting clamp for the linear rails. The rails should be a tight slip-fit into the center hole, then clamped using an 8-32 screw.



**Figure B.25** An adapter plate was not necessarily required, as most of the holes could have been made directly into the old leveling plate, but it was deemed simpler to make this than risk damaging the leveling plate by re-machining it.



**Figure B.26** The new tapping plate is shown in drawing 0027. This was a much simpler design than the tapping plate/mounting brackets designed in the prototype.



**Figure B.27** The shaft was purchased as a single piece of material, approximately 59" long from VXB.com. It was then cut to the correct size. Refer to the product webpage for hardness and material grades (VXB Ball Bearings, 2010).



**Figure B.28** The first half of the shock absorber mount is shown in drawing 0030. The shock absorber is mounted into the 5/16" thru hole, and the mating clamp piece is used to secure it to one of the two vertical linear guides.



**Figure B.29** The second piece of the shock absorber clamp is detailed in drawing 0031. Four 8-32 machine screws are used to attach this to its mating part shown in drawing 0030.



**Figure B.30** With the removal of the side walls from the design prototype, it was necessary to design a mounting plate for the air pack. Drawing 0032 shows the new mount design.



**Figure B.31** The read head for the encoder mounts to the part shown in drawing 0033. The sensor comes equipped with two placement pins which help with the alignment.



**Figure B.32** The codestrip clamps were designed to allow for some adjustment of the codestrip once it was in position. It simply clamps on top of the strip using two 10-32 machine screws.



**Figure B.33** Drawing 0036 shows the 3-view drawing of the codestrip mount. This slips over the linear rail, and is secured by a <sup>1</sup>/<sub>4</sub>-20 brass tipped set screw onto the rail. The codestrip is then clamped on using part 0035.



**Figure B.34** Drawing 0037 was designed because the cylinder air fittings dipped below the bottom of the air cylinder. The spacer was needed to keep the fitting from interfering with the leveling plate.



**Figure B.35** The sample container base was designed to mate to the tapping plate using four 10-32 screws.



**Figure B.36** The sample container core is glued to the center of the base, creating a complete sample container. The system was designed to allow for a single style base that could mate to many different size cores..
# **APPENDIX C**

# PNEUMATIC DIAGRAM

This is the pneumatic diagram for the air supply feeding the prototype.



Figure C.1 Schematic for pneumatic system.

# APPENDIX D

# **ELECTRICAL DIAGRAMS**



Figure D.1 Electrical schematic for the first prototype.



Figure D.2 Electrical schematic for the second prototype.

# **APPENDIX E**

## **PROGRAM SOURCE CODE**

## E.1 Prototype Source Code

/\*

```
Tap
 Outputs a pulse to a cylinder, then reads the subsequent accellerometer
 values and stores the maximum value in an array table
 Value of array(tapNumber) is equal to the maximum z-axis acceleration
*/
const int relayPin = 4; // Reay connected to digital pin 4
const int limitPin = 3;
                        // Limit connected to digital pin 3
const int switchPin = 2; // Switch connected to digital pin 2
int switchState = 0;
                        // variable for reading the switch status
                       // variable for reading the limit
int limitState = 0;
long accelValue = 0;
                          // variable for reading the accelerometer
                       // variable for reading the potentiometer
int potValue = 0;
int cycleCount = 0;
long adjustedAccel = 0;
long accelCalibration = 0;
unsigned long pitchTimer = 0;
                                   // variable for setting delay time
unsigned long time = 0;
// The setup() method runs once, when the sketch starts
void setup() {
 // initialize the digital pin as an output:
 pinMode(relayPin, OUTPUT);
 // initicalize the digial pin as an input:
 pinMode(limitPin, INPUT);
 pinMode(switchPin, INPUT);
 // initialize the serial output
 Serial.begin(9600);
 cvcleCount=0;
 accelCalibration = analogRead(0);
// the loop() method runs over and over again,
// as long as the Arduino has power
void loop()
 switchState=0;
 do {
  // Read the state of the switch
  switchState = digitalRead(switchPin);
```

```
} while (switchState == LOW);
cycleCount=cycleCount+1;
potValue = analogRead(1);
pitchTimer = (potValue*5)+millis();
digitalWrite(relayPin, HIGH); // set the relay on
do
{
 // read the accel input into a variable:
 accelValue = analogRead(0);
 adjustedAccel = accelValue - accelCalibration;
 // - 500;
 // wait 10 milliseconds for the analog-to-digital converter
 // to settle after the last reading:
 delay(2);
 limitState = digitalRead(limitPin);
 if (limitState == HIGH) { digitalWrite(relayPin,LOW); }
 time=millis();
 // print the result:
 Serial.print(cycleCount, DEC);
 Serial.print(",");
 Serial.println(adjustedAccel, DEC);
 // Serial.print("Time: ");
 // Serial.println(time, DEC);
 // Serial.print("Pitch: ");
 // Serial.println(pitchTimer, DEC);
```

```
} while (time < pitchTimer);
digitalWrite(relayPin, LOW);
}
```

```
E.2 Source Code for Revised Prototype
```

# /\*

```
Tap-it
Source code for a tapped densification apparatus.
Sends an impulse to a cylinder, reads encoder values
and writes the results with a time stamp to a microSD card.
*/
```

// Used for accessing the microSD #include <SdFat.h> #include <SdFatUtil.h> #include <avr/pgmspace.h>

```
prog_char menu1[] PROGMEM = "Start Test";
prog_char menu2[] PROGMEM = "Cycles";
prog_char menu3[] PROGMEM = "Samples";
prog_char menu4[] PROGMEM = "Delay";
PROGMEM const char *menu table[] = {
 menu1,
 menu2,
 menu3,
 menu4};
prog_char error1[] PROGMEM = "err card init";
prog_char error2[] PROGMEM = "err volume init";
prog_char error3[] PROGMEM = "err root error";
prog_char error4[] PROGMEM = "err file create";
PROGMEM const char *error table[] = {
 error1,
 error2,
 error3,
 error4};
 /*
prog char units1[] PROGMEM = " Taps";
prog_char units2[] PROGMEM = " Samples";
prog_char units3[] PROGMEM = " ms";
PROGMEM const char *units table[] = {
 units1,
 units2.
 units3};
*/
char buffer[16];
// Set up the microSD
Sd2Card card;
SdVolume volume;
SdFile root;
SdFile file;
// Definitions for LCD control
#define SPECIAL CONTROL 0x7C
#define DISPLAY CONTROL 0xFE
#define CLEAR
                     0x01
```

#define numRows 2
#define numCols 16

// Define digital pin numbers
#define encoder0PinA 2
#define encoder0PinB 3
#define limitPin 4
#define relayPin 5
#define LEDpin 9
#define SPIpin 10

// Define analog pin numbers#define btnUp A0#define btnEnter A1#define btnDown A2

// Define constants for reading key-press#define KeyUp 1#define KeyDown 2#define KeyEnter 3

// Define limits for mapping encoder distance
#define countsMax 1645
#define countsMin 0
/\*
Range is in inches \* 1000. Since the mapping function only works
on integers, all resulting values must be divided by 1000 for true
distance. This produces a reading with an resolution of 0.001"
\*/

#define rangeMax 2750 #define rangeMin 0

// Define maximum number of cycles allowed
#define MAX\_CYCLES 10000
#define MAX\_READINGS 100
#define MAX\_TIMEDELAY 250

// Sets total number of items in each menu
#define MENU\_ITEMS 4

// Variables for system settings
// Defaults value set here
int tapsInt = 50;
int readings = 50;
int timeDelay = 10;

```
byte menuItem = 1;
int currentCycle = 1;
// Array used to store the encoder readings
int encoderValues[MAX READINGS];
volatile int encoder0Pos = 0;
boolean A set = false;
boolean B set = false;
// Array for storing stample time.
int sampleTime[MAX READINGS];
* Functions for control of the microSD card
// store error strings in flash to save RAM
#define error(s) error P(PSTR(s))
void error P(const char *str) {
 PgmPrint("error: ");
 SerialPrintln P(str);
 if (card.errorCode()) {
  PgmPrint("SD error: ");
  Serial.print(card.errorCode(), HEX);
  delay(10);
  Serial.print(',');
  delay(10);
  Serial.println(card.errorData(), HEX);
  delay(10);
 while(1);
// Write CR LF to a file
void writeCRLF(SdFile &f) {
 f.write((uint8_t *)"\r\n", 2);
```

/\*

\*/

}

}

```
}
// Write an unsigned number to a file
void writeNumber(SdFile &f, uint32 t n) {
 uint8_t buf[10];
 uint8 t i = 0;
```

```
do {
  i++;
  buf[sizeof(buf) - i] = n\%10 + '0';
  n = 10;
 } while (n);
 f.write(&buf[sizeof(buf) - i], i);
}
// Write a string to a file
void writeString(SdFile &f, char *str) {
 uint8 t n;
 for (n = 0; str[n]; n++);
 f.write((uint8 t *)str, n);
}
/*
* Functions for control of the LCD screen
*/
void lcdSendControl(char c) {
 Serial.print((char)DISPLAY CONTROL);
 delay(10);
 Serial.print(c);
 delay(10);
}
void lcdClear() {
 lcdSendControl(CLEAR);
}
void lcdCursor(int line, int col) {
 line %= numRows;
 col %= numCols;
 byte offset = ((line\%2)*64) + (line > 1 ? 20 : 0);
 lcdSendControl((char)(offset + col + 128));
}
/*
* Functions for running the actual test
*/
void runTest() {
 digitalWrite(LEDpin,HIGH);
 int CyclesToRun = tapsInt + currentCycle;
```

```
while (currentCycle < min(CyclesToRun,10000)) {
  // Draw screen
  lcdClear();
  lcdCursor(0,0);
  Serial.print("Cycle Count:");
  lcdCursor(0,12);
  Serial.print(currentCycle);
  // Send pulse to plate and save results to disk
  saveTap(tapPlate());
 }
digitalWrite(LEDpin,LOW);
}
long tapPlate() {
 int time, pitch;
// encoder pin on interrupt 0 (pin 2)
 attachInterrupt(0, doEncoderA, CHANGE);
// encoder pin on interrupt 1 (pin 3)
 attachInterrupt(1, doEncoderB, CHANGE);
 encoder0Pos = 0;
 time=millis();
 digitalWrite(relayPin,HIGH);
 for(int x = 0; x < readings; x++) {
  sampleTime[x] = millis() - time;
  encoderValues[x] = encoder0Pos;
  if (digitalRead(limitPin)) digitalWrite(relayPin,LOW);
  delay(timeDelay);
 }
 detachInterrupt(0);
 detachInterrupt(1);
pitch = millis() - time;
return pitch;
}
void checkTap() {
 int x100=0, x10=0;
 char name[] = "TAP0000.TXT";
 for (int i = 1; i \le 9999; i + +) {
```

```
name[3] = i/1000 + '0';
  x100 = i\%1000;
  name[4] = x100/100 + 0';
  x10 = x100\%100;
  name[5] = x10/10 + 0';
  name[6] = x10\%10 + '0';
  lcdCursor(1,0);
  Serial.print(i);
  if (file.open(root, name, O_CREAT | O_EXCL | O_WRITE)) {
   currentCycle = i;
   break;
  }
  //file.open(root, name, O READ);
  //if (!file.isOpen()) {
  // currentCycle = i;
  // break;
  //}
 }
 file.remove();
 delay(2000);
}
void saveTap(long pitch) {
 int x100=0, x10=0;
 int reading = 0;
 char name[] = "TAP0001.TXT";
 name[3] = currentCycle/1000 + '0';
 x100 = currentCycle%1000;
 name[4] = x100/100 + 0';
 x10 = x100\%100;
 name[5] = x10/10 + 0';
 name[6] = x10\%10 + 0';
 file.open(root, name, O CREAT | O EXCL | O WRITE);
 if (!file.isOpen()) {
  lcdClear();
  lcdCursor(0,0);
  strcpy_P(buffer, (char*)pgm_read_word(&(error_table[3])));
  Serial.print(buffer);
  delay(1000);
 }
// write name to file
 writeString(file,name);
 writeCRLF(file);
```

```
// 2nd line is total pitch
 writeString(file, "Pitch (ms): ");
 writeNumber(file, pitch);
 writeCRLF(file);
 // Line for data header
 writeString(file, "Sample, Time (ms), Encoder (in*1000)");
 writeCRLF(file);
 for (int i = 0; i < readings; i++) {
  // Scale encoder values, and trap the minimum value at 0.
  reading = map(encoderValues[i],countsMin,countsMax,rangeMin,rangeMax);
  reading = max(reading,0);
  // Write sample
  writeNumber(file, i+1);
  writeString(file, ",");
  writeNumber(file, sampleTime[i]);
  writeString(file,",");
  writeNumber(file, reading);
  writeCRLF(file);
 }
 currentCycle++;
 // close file and force write of all data to the SD card
 file.close();
/*
This is a short program to define the polling of the buttons. It was mainly writen to allow
for a break in LCD update. Constant refreshing of the LCD dims the display.
*/
byte pollButtons() {
 byte which = 0;
 if (!digitalRead(btnEnter)) {
  which = KeyEnter;
  while(!digitalRead(btnEnter));
 } else if (!digitalRead(btnUp)) {
  which = KeyUp;
  while(!digitalRead(btnUp));
```

```
} else if (!digitalRead(btnDown)) {
```

```
which = KeyDown;
```

}

```
while(!digitalRead(btnDown));
 }
return which;
}
/*
Functions for drawing and using the main menu
*/
void drawMenu() {
 if(menuItem == 0) menuItem = MENU ITEMS;
 if(menuItem > MENU ITEMS) menuItem = 1;
lcdClear();
 lcdCursor(0,0);
 strcpy P(buffer, (char*)pgm read word(&(menu table[menuItem-1])));
 Serial.print( buffer );
 if (menuItem > 1) {
  lcdCursor(1,0);
  Serial.print(":");
 }
 lcdCursor(1,1);
 delay(100);
 switch(menuItem) {
  // Case 1 - Start Test
  case 1:
   break;
  // Cycles
  case 2:
   Serial.print(tapsInt);
   //strcpy P(buffer, (char*)pgm_read_word(&(units_table[0])));
   //Serial.print(buffer);
   Serial.print(" Taps");
   break;
  // Samples
  case 3:
   Serial.print(readings);
   //strcpy P(buffer, (char*)pgm read word(&(units table[1])));
   //Serial.print(buffer);
   Serial.print(" Samples");
   break;
```

```
// Time Dealy
```

```
case 4:
   Serial.print(timeDelay);
   //strcpy P(buffer, (char*)pgm read word(&(units table[2])));
   //Serial.print(buffer);
   Serial.print(" ms");
   break;
}
}
void useMenu() {
 switch(menuItem) {
  case 1:
   runTest();
   break;
  case 2:
   setCycles();
   break;
  case 3:
   setSamples();
   break;
  case 4:
   setDelay();
   break;
 }
}
/*
Functions for changing the settings in the main menu
*/
void setCycles()
ł
byte keypress;
drawCyclesMenu();
 do \{
  if (keypress == KeyUp) {
   tapsInt++;
   drawCyclesMenu();
  }
  else if (keypress == KeyDown) {
   tapsInt--;
   drawCyclesMenu();
  }
  keypress = pollButtons();
 } while (keypress != KeyEnter);
```

}

}

```
void drawCyclesMenu() {
 // Constrain tapsInt to the acceptable range
 tapsInt = constrain(tapsInt,1,MAX_CYCLES);
// Draw the screen
lcdClear();
 lcdCursor(0,0);
strcpy P(buffer, (char*)pgm_read_word(&(menu_table[1])));
 Serial.print(buffer);
 lcdCursor(1,0);
 Serial.print(">");
 Serial.print(tapsInt);
 Serial.print(" Taps");
//strcpy P(buffer, (char*)pgm read word(&(units table[0])));
//Serial.print(buffer);
void setSamples()
 byte keypress;
 drawSamplesMenu();
 do {
  if (keypress == KeyUp) {
   readings++;
   drawSamplesMenu();
  }
  else if (keypress == KeyDown) {
   readings--;
   drawSamplesMenu();
  }
  keypress = pollButtons();
 } while (keypress != KeyEnter);
}
void drawSamplesMenu() {
// Constrain tapsInt to the acceptable range
 readings = constrain(readings,1,MAX READINGS);
// Draw the screen
 lcdClear();
 lcdCursor(0,0);
 strcpy_P(buffer, (char*)pgm_read_word(&(menu_table[2])));
 Serial.print(buffer);
```

```
lcdCursor(1,0);
 Serial.print(">");
 Serial.print(readings);
 Serial.print(" Samples");
 //strcpy P(buffer, (char*)pgm read word(&(units table[1])));
 //Serial.print(buffer);
}
void setDelay()
 byte keypress;
 drawDelayMenu();
 do {
  if (keypress == KeyUp) {
   timeDelay++;
   drawDelayMenu();
  }
  else if (keypress == KeyDown) {
   timeDelay--;
   drawDelayMenu();
  }
  keypress = pollButtons();
 } while (keypress != KeyEnter);
}
void drawDelayMenu() {
 // Constrain tapsInt to the acceptable range
 timeDelay = constrain(timeDelay,1,MAX TIMEDELAY);
 // Draw the screen
 lcdClear();
 lcdCursor(0,0);
 strcpy P(buffer, (char*)pgm read word(&(menu table[3])));
 Serial.print(buffer);
 lcdCursor(1,0);
 Serial.print(">");
 Serial.print(timeDelay);
 Serial.print(" ms");
 //strcpy P(buffer, (char*)pgm read word(&(units table[2])));
 //Serial.print(buffer);
}
// Interrupt on A changing state
void doEncoderA(){
```

```
// Test transition
```

```
A set = digitalRead(encoder0PinA) == HIGH;
 // and adjust counter + if A leads B
 encoder0Pos += (A set != B set) ? +1 : -1;
}
// Interrupt on B changing state
void doEncoderB(){
 // Test transition
 B set = digitalRead(encoder0PinB) == HIGH;
 // and adjust counter + if B follows A
 encoder0Pos += (A set == B set) ? +1 : -1;
}
void setup() {
 // Set up pins
 // Set inputs
 pinMode(btnUp, INPUT);
 digitalWrite(btnUp, HIGH);
 pinMode(btnEnter, INPUT);
 digitalWrite(btnEnter, HIGH);
 pinMode(btnDown, INPUT);
 digitalWrite(btnDown, HIGH);
 pinMode(limitPin, INPUT);
 pinMode(encoder0PinA, INPUT);
 pinMode(encoder0PinB, INPUT);
 // Set outputs
 pinMode(relayPin, OUTPUT);
 digitalWrite(SPIpin, LOW);
 pinMode(SPIpin, OUTPUT);
 pinMode(LEDpin, OUTPUT);
 Serial.begin(9600);
 lcdClear();
 Serial.print((char)SPECIAL CONTROL);
 Serial.print((char)157);
 delay(5);
 lcdClear();
 lcdCursor(0,numCols/2-3);
 Serial.print("Tap-It");
 lcdCursor(1,numCols/2-2);
 Serial.print("NJIT");
 delay(2000);
```

```
// initialize the SD card
 if (!card.init()) {
  lcdClear();
  lcdCursor(0,0);
  strcpy P(buffer, (char*)pgm read word(&(error table[0])));
  Serial.print(buffer);
  delay(10);
 }
// initialize a FAT volume
 if (!volume.init(card)) {
  lcdClear();
  lcdCursor(0,0);
  strcpy P(buffer, (char*)pgm read word(&(error table[1])));
  Serial.print(buffer);
  delay(10);
 }
 // open the root directory
 if (!root.openRoot(volume)) {
  lcdClear();
  lcdCursor(0,0);
  strcpy P(buffer, (char*)pgm read word(&(error table[2])));
  Serial.print(buffer);
  delay(10);
 }
 lcdClear();
lcdCursor(0,0);
 Serial.print("Checking Card");
 checkTap();
}
void loop() {
 byte which key = 0;
 drawMenu();
 while(1) {
  switch (whichkey) {
   case KeyUp:
    menuItem--;
    drawMenu();
    break;
   case KeyDown:
    menuItem++;
```

```
drawMenu();
break;
case KeyEnter:
useMenu();
drawMenu();
break;
default:
break;
}
whichkey = pollButtons(); // Get a keypress
}
```

#### **APPENDIX F**

### **INSTRUCTION MANUAL**

### F.1 Installation

Operation of the tap densification testing apparatus requires an air supply with the necessary pressure to ensure the required experimental force of impact, and a standard 120VAC household outlet. To obtain data from the apparatus, a standard microSD or SD card reader and computer are required. Installation of the machine is designed to be a relatively simple affair:

- 1. Place the apparatus on a stable, steady surface.
- 2. Loosen the (4) screws securing the leveling plate
- 3. Adjust the leveling plate until the plate is level.
- 4. Tighten the (4) screws to secure the leveling plate.
- 5. Attach air supply to regulator input.
- 6. Plug in the apparatus and control device.

### F.2 Maintenance

Like all machines, standard maintenance procedures should be followed to keep the machine operating at peak performance for the life of the device. In this case, it may be necessary to monitor and replace certain high-wear components every so often. These include the shock absorber and the cylinder bumper. Frequent exposure to impact forces over time may reduce the life of these components. The air cylinder may need to be

monitored for damage or wear but replacing this should be a rare occurrence if the bumper is properly maintained.

The linear bearings require lubrication on a regular basis. It is recommended these be lubricated once before performing any experiments, and again after the experiments have been performed and the apparatus is going to be put in storage. WD40 is not recommended for ballbearing ways due to the fact that it can get sticky and gummy over long periods of time. This is counterproductive to the bearings. Proper lubrication will not only keep the motion smooth and unhindered, but should also reduce corrosion on the bearings and hardened steel rail.

As always, keep the machine clean and free of dust and debris. The powdercoat surface should protect much of the surface from corrosion and contamination, but wiping the apparatus down with a dry or slightly damp cloth may be beneficial to long term reliability.

#### **F.3** Operating Instructions

The operation of the apparatus is fairly simple. The LCD displays a menu for settings and to start the test, while three buttons control the menu. These buttons are up, down, and select. To navigate the menu, press up or down. When the desired menu item appears, press select. If the menu item is a value setting, the starting character on the menu's second line will change from ":" to ">". At this point, pressing up or down will increment or decrement the value by 1 each press. Pressing select again returns to the menu.

There are three settings that can be changed for each experiment. The first is the number of taps to perform, up to a maximum of 9999. The second is the number of samples to capture during each tap. A maximum of 100 samples can be captured during each tap. Physical memory limitations of the controller make it unwise to go any higher than this. The last value to be changed is a delay time in milliseconds. The maximum delay is 250 ms.

When a test is started, the controller zeros the encoder position, and captures a time value using the system clock in the microcontroller. Using this time value as time 0, it then takes a reading from the limit switch, stores an incremental time value, and stores the current encoder position. After these are captured, it then waits for a period of time determined by the user in the delay time. The controller continuously loops through the sensors and encoder position until the number of samples captured equals the user entered value. The microcontroller then stores these values in a file labeled TESTXXXX.txt, where XXXX is an incremental value.

To read the data:

- Remove power from the device.
- Remove the memory card.
- Place memory card into a card reader or adapter.
- Open the desired text file in Excel using "Text (.csv)" file type.
- Add scaling factors and calculations where necessary.

The timestamp is measured in milliseconds, and the distance is a unit of inches multiplied by a factor of 1000. In order to calculate time, distance, velocity and

acceleration in inches and seconds, simply divide both the encoder reading, and timestamp by 1000.

## **APPENDIX G**

## LIST OF VENDORS

AVNet www.avnet.com Part Number: AEDS-9461-P10 Description: Small Optical Encoder Mods List Price: \$4.31 Assembly P/N: 0137 Bimba www.bimba.com Part Number : EF-2525-BEM\*\* Description: Air Cylinder, 1" bore, 1" stroke List Price: \$59.15 Assembly P/N: 0123 Electronic Goldmine www.goldmine-elec.com/ Part Number: G15602 Description: Photographic Precision Encoder Strip List Price: \$1.98 Assembly P/N: 0135 IGUS www.igus.eu Part Number: NK02-17-1-100 Description: Linear Rail, 1 carriage. List Price: ~\$40 Assembly P/N: 0115 SMC Corporation www.smcusa.com Part Number: RBC0806S Description: Shock Absorber, 8mm thread, 6 mm stroke. List Price: ~\$28 Assembly P/N: 0136 Part Number: AW20-N01EH-CZ\*\* Description: Filter/Regulator List Price: ~\$30 Assembly P/N: 0122

#### www.smcusa.com

MACValves

Part Number:45A-AA2-DAAA-1CM\*\*Description:Solenoid, 4-way, NPTF, Spring ReturnList Price:~\$37Assembly P/N:0109

# SparkFun

# www.sparkfun.com

Notes: Many of the items ordered from this vendor are not listed here. Typical electronics components such as switches, resistors, LED's and capacitors were left off this list.

Part Number:	DEV-00666
Description:	Arduino Main Board
List Price:	\$29.95
Part Number:	COM-00101
Description:	Relay SPST-NO Sealed -30A
List Price:	\$3.95
Part Number:	COM-09096
Description:	Relay Control PCB
List Price:	\$3.95
Part Number:	SEN-00848
Description:	Dual Axis Accelerometer Breakout Board – ADXL321 +/-18g
List Price:	\$29.95
Part Number:	COM-08163
Description:	Flash Memory – microSD 1GB
List Price:	\$9.95
Part Number:	TOL-00298
Description:	Wall Adapter Power Supply – 9VDC 650mA
List Price:	\$5.95
Part Number:	DEV-09802
Description:	microSD Shield
List Price:	\$14.95
Part Number:	LCD-09068
Description:	Serial Enabled 16x2 LCD – Red on Black, 3.3v
List Price:	\$24.95
Part Number:	DEV-07914
Description:	Arduino ProtoShield Kit
List Price:	\$16.95

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Part Number:Kit8083Description:NB Linear Systems: SWF6 3/8" Ball BushingsList Price:\$24.95Assembly P/N:0134

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Part Number:Kit8005Description:NB Linear Systems: SFW6: Linear Motion ShaftList Price:\$29.95Assembly P/N:Used in 0028

\*\*These and any other purchasable items including fittings and fasteners were donated by Glebar Co., Inc., of Franklin Lakes, NJ. The ones listed here are for re-ordering information in case of malfunction.

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### REFERENCES

- AllDataSheets.com. (2010). *EM84510FP PS/2 SCROLLING MOUSE CONTROLLER ELAN Microelectronics Corp*. Retrieved November 1, 2010, from AllDataSheets: http://www.alldatasheet.com/view.jsp?Searchword=EM84510FP
- Analog Devices. (2004, September). *Dual Axis Accelerometer Breakout Board ADXL321 +/-18g.* Retrieved October 1, 2010, from SparkFun: http://www.sparkfun.com/datasheets/Accelerometers/ADXL320\_0.pdf
- Antech. (2010). *Tapped Density Tester for Powders: Series JV*. Retrieved December 5, 2010, from Antech Ireland: http://www.antech.ie/tapdens.shtml
- Arduino. (n.d.). Arduino Duemilanove. Retrieved October 1, 2010, from Adruino: http://arduino.cc/en/Main/ArduinoBoardDuemilanove
- Avago Technologies. (2010). *AEDS-9641-P10*. Retrieved November 10, 2010, from Avego Technologies: http://www.avagotech.com/pages/en/motion\_control\_encoder\_products/increment al\_encoders/transmissive\_encoders/aeds-9641-p10/
- Avnet. (2010). *AEDS-9641-P10*. Retrieved November 10, 2010, from Avnet: http://www.avagotech.com/docs/AV01-0286EN
- Bimba. (2010). *Bimba EF1 Cylinders*. Retrieved October 1, 2010, from Bimba: http://www.bimba.com/Products/FlatCylinders/EF1Cylinders/
- Distek. (2010). *Two-Station Tap Density Tester*. Retrieved December 5, 2010, from Distek: Creating a Stir: http://www.distekinc.com/products/td\_1020.htm
- Electrolab. (2010). *ETD-1020*. Retrieved December 5, 2010, from Electrolab: http://www.electrolabindia.com/Features.aspx?ProductId=24&SubCategoryId=77
- Electronic Goldmine. (2010). *Photographic Precision Encoder Strip*. Retrieved November 10, 2010, from Electronic Goldmine: http://www.goldmine-elecproducts.com/prodinfo.asp?number=G15602
- Fahey, C. (n.d.). *PS2 mouse and BASIC Stamp computer*. Retrieved November 1, 2010, from colinfahey.com: http://www.colinfahey.com/ps2\_mouse\_and\_basic\_stamp\_computer/ps2\_mouse\_and\_basic\_stamp\_computer\_en.htm

- Greiman, B. (2010). *sdfatlib: A FAT16/FAT32 Arduino library for SD/SDHC cards*. Retrieved November 27, 2010, from Google Project Hosting: http://code.google.com/p/sdfatlib/
- IGUS. (2010). *DryLin*® *N Low profile linear guide system NK-02-17*. Retrieved March 2010, from IGUS: http://www.igus.eu/wpck/default.aspx?PageNr=1976
- Krasnow, B. (2010, February 26). *Linear position tracking with a quadrature encoder*. Retrieved November 10, 2010, from Ben Krasnow @ Blogspot: http://benkrasnow.blogspot.com/2010/02/linear-position-tracking-with.html
- Quantachrome. (2010). Autotap<sup>™</sup> and Dual Autotap<sup>™</sup>: Tap Density Analyzers. Retrieved October 5, 2010, from Quantachrome Instruments: http://www.quantachrome.com/materials\_applications/tap\_density.htm
- Ratnaswamy, V. (2010). Stochastic and Deterministic Dynamics Investigation of the Microstructure of Granular Materials. Newark, NJ: New Jersey Institute of Technology.
- SMC Corporation. (2010). *RB*, *Shock Absorber*. Retrieved November 10, 2010, from SMC Product Selector: http://content.smcetech.com/pdf/RB.pdf
- SMC Corporation. (2006). SMC Product Selector, AW, North American & European Specifications. Retrieved October 1, 2010, from SMC Airline Equipment: http://content.smcetech.com/pdf/aw.pdf
- Softwarestorage. (2008, September 15). *Wikipedia*. Retrieved October 4, 2010, from User:Softwarestorage/Tapped density: http://en.wikipedia.org/wiki/User:Softwarestorage/Tapped\_density
- Sotax. (2010). *TD1*. Retrieved December 5, 2010, from Sotax: Solutions for Pharmaceutical Testing: http://www.sotax.com/Tap-density.118.0.html
- SparkFun Electronics. (2010). *microSD Shield*. Retrieved November 27, 2010, from SparkFun Electronics: http://www.sparkfun.com/products/9802
- SparkFun Electronics. (2006, July 5). SerLCD v2.5. Retrieved November 27, 2010, from SparkFun Electronics: http://www.sparkfun.com/datasheets/LCD/SerLCD\_V2\_5.PDF
- Varian. (2010, November). Tapped Density Tester 70-9010. Retrieved December 5, 2010, from Agilent Technologies: http://www.chem.agilent.com/Library/usermanuals/Public/70-9010J\_Tapped\_Density\_Tester\_Op\_Man.pdf

VXB Ball Bearings. (2010). *NB Linear Systems:SFW6:3/8" Linear Motion Shaft 59.06" Length.* Retrieved October 8, 2010, from VXB.COM Ball Bearings: http://www.vxb.com/page/bearings/PROD/3-8inchLinearMotionSystems/Kit8005