CASE WESTERN RESERVE UNIVERSITY

Senior Project Final Report

Miniature CNC Mill Engraver

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EMAE 398: Senior Project

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5/5/2010

Abstract

This project will seek to simplify a computer numerically controlled (CNC) mill so that it can be produced inexpensively and on a much smaller scale. The cost of the machine was kept as low as possible (under $400). The size of the machine was designed so that it would fit on something like a work bench, so the dimensions were 18” by 18”. The whole project is a design and fabrication exercise, and it was a success. The CNC mill can etch designs into Aluminum, or cut softer materials such as HDPE.

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Introduction

A computer numerically controlled mill is a highly complex piece of machinery. They can cost tens of thousands of dollars and take up large amounts of space. Both of these factors make them unreasonable for the home. The goal was to create something that was both inexpensive and compact. To keep costs low a Dremel tool would be used as the cutting tool. This would limit amount that the machine would be able to cut, so the machine may be better designed for etching instead of heavy machining.

Design

There were a few major decisions that needed to be made prior to the design process. The first being whether the cutting bed or the gantry and tool would be mobile. The second major decision was how the mobile parts of the machine were going to be driven. The transfer of power was also another important factor that needed to be dealt with. Another decision was how to keep the moving components linear.

The main decision that would influence every part of the design process was whether to choose a mobile gantry and tool with a stationary bed, or a stationary tool and gantry with a mobile bed. For the sake of simplicity the choice was made to use a mobile gantry and tool with a stationary bed. This seemed to be the most intuitive method. After doing some research online the size of the machine also plays into this decision. A smaller machine would be easier to use a mobile bed. As the size of the bed increases though, it becomes more complicated for the bed to be mobile. Since the cutting area would be nearly 18” x 18” the size of this project also indicated that a mobile gantry and tool should be used.

The problem of how to drive the mobile gantry was the next issue to tackle. After researching, it seemed there was only two real options for how accomplish steady and consistent movement of the gantry. The first option was to use gears and sprockets. The other option was to use threaded rod to drive the gantry forward and back. For the sake of simplicity, the threaded rod was chosen. It would be much easier to buy threaded rod, then simply tap a hole or have a threaded insert. When the threaded rod would spin, it would push the tapped drive piece one way or another, depending on which way the rod spins.

Now that the threaded rod was chosen, it must be determined how to get the power from the motor to the threaded rod. Once again there are two main choices. One option is to have a belt and pulley system. This system would be a bit more complex, and has the possibility of the belt slipping, which would be a big problem. The other option is to have the threaded rod directly linked to the motor. The direct linkage of the motor and rod would require design considerations and adjustments, but would be the easiest in the long run. This was the option that was chosen. The threaded rod had a concentric hole bored in it, then a small tapped hole drilled in the side so that a set screw could be inserted locking the shaft of the motor to the threaded rod.

The last major decision that needed to be dealt with was how to keep the mobile parts linear. This is the most complicated of problems encountered so far. For the CNC machine to work as expected, the gantry must move in the X, Y and Z plane perfectly. There are many solutions to this problem, but something simple and straightforward is needed for it to be successful. One solution that is commonly used is to have a track that rolling ball bearings move along as shown in *figure 1*.

Figure 1 – Rolling Bearings on a Track

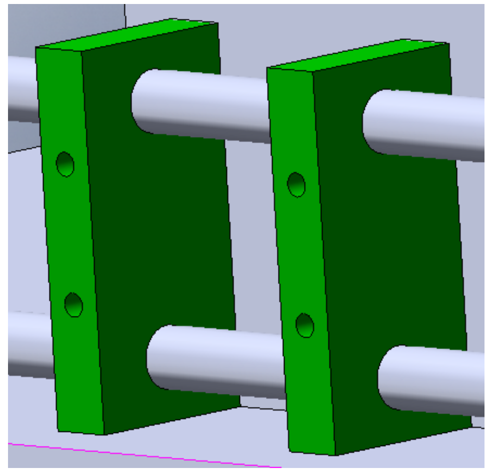

Figure 2 – Sliders (Highlighted in Green)

The problem with this solution is that any nonlinearity could easily knock the bearings off of this track rendering them useless. The method that was decided upon was to have some sort other sort of slider that would guide the movement along a track (shown in *figure 2*). These sliders would be made of High Density Polyethylene (HDPE) so that they would easily slide along the metal rails.   This system comes with its own set of drawbacks. If the gantry is not rigid enough, or the rails not close enough to parallel, the sliders may bind, causing the machine to lock.

There were a few components necessary to the construction of the CNC machine that there was no design involved for. These include the stepper motors used to propel the machine, the stepper motors controller, and the cutting tool. The motors are Nema 23 stepper motors. They are made by Vexta and can be wired both bipolar and unipolar configurations. They have a step size of 1.8° with a maximum holding torque of 10.4 lb-in. A full data sheet can be found in the *Appendix*. The stepper motor controller is a 3 – axis Mechatronics micro stepper motor driver. It is a two phase bipolar driver with adjustable step resolution, and more importantly individual heat sinks per axis. Again a full data sheet can be found in the *Appendix*. The cutting tool will be a Dremel 300 series, using the “flex shaft” attachment. This tool should allow customization and a wide variety of cutting tools for various types of cutting surfaces.

Methods

Even when the CNC machine is heavily simplified, it still consists of many components. Each one of these components was designed carefully, and most of them were revised several times to ensure the best operation possible. The majority of this section will describe the initial design and reasoning behind it. Drawings located in the appendix will show each component in more detail.

Rail Bracket

The rail brackets were not part of the early plans. The rails that the sliders would travel along would be mounted directly to the cutting table using clamps of some sort, and there would be only one rail per side. As the design evolved, it was decided that two rails per side, placed vertically above each other would help stabilize the design. This decision meant that there would need to be some sort of bracket to hold these rails parallel to, and above the cutting table.

Motor Bracket

The motor bracket was designed to serve two purposes. As the name implies, one of the purposes was to create something that the stepper motors could be mounted to. For the threaded rod to run in between the two rails, the motor bracket would also need to support the rails. Basically this part combines the rail bracket with a motor mount.

Sliders

It was always planned to have the sliders made out of HDPE. This way they would easily slide on the metal rails. Since the initial plan was to have only a single rail per side, the sliders evolved along with the plan to have two rails per side. Several designs were explored and later revamped because this is such a vital part of the project. It needed to support a good deal of weight, while at the same time be very stable.

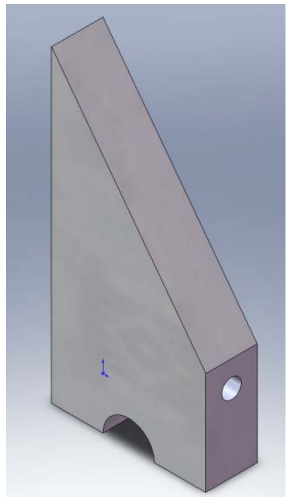

Figure 3 – Early Slider Design

Gantry Support

Since the gantry was designed to move it needs to meet three requirements. It needs to be light enough to be moved and not bog down the sliders. It needs to be strong enough to hold the weight of both the Y and Z axes. It also needs to be rigid. If the gantry support is not rigid it could flex sending the X or Y axes out of parallel. The gantry support on one side would also need to be designed so that the motor that controls the Y axis could be mounted.

Inserts and Z Drive Block

The threaded inserts and the Z drive block are crucial to driving the machine. The inserts are used in both the X and Y axes, while the Z drive block is for the Z. They all had an interior hole that is threaded. The inserts are bonded to a slider and the Y block for the X and Y axes respectively. The Z drive block is bolted to the Z block. This way when the threaded rod is spun by the step motors, it causes the threaded rod and therefore insert or block to respond with movement.

Y Block

The Y block works on the same principle as the sliders. It is be made of HDPE and is suspended by two metal rails aligned vertically. In between the rails a threaded rod runs that would supply the propulsion. The Y Block went through a great deal of revision because it supports the entire Z axis including the Z motor. To save on material and to make the Z axis travel smoother and more linearly, the Y block was changed to be composed of three pieces. The main piece is the one that slides along the rails, while there are two blocks attached to it. Each of these blocks is slotted so that the Z block fits in the slot between them, making the Z axis movement smooth and linear.

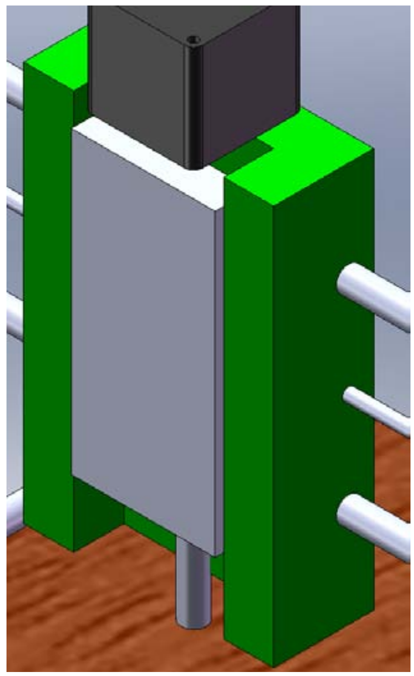

Figure 4 – Early Y and Z Block Design

Z Block

The Z block isbasic. Since the Y block ensured that the Z block travels smoothly and linearly, there is not much needed to design around. The main thing that needed to be considered for the design is that the Z block be large enough for the cutting tool to be easily mounted to it.

Results

The entire CNC machine was fabricated over the course of a little over a month. The materials it is composed of included steel rails, High Density Polyethylene Sliders and various aluminum parts. All the parts with the exception of the cutting table were fabricated in the Bingham machine shop under the supervision of Jim Drake and Adam Jones. The cutting table was cut using the CNC plasma cutter in Reinberger.

When the CNC machine was initially assembled it had a few issues. The largest was the binding of the sliders and rails. This was caused by a slight flexing of the gantry (because it was only driven on one side of the X axis) as well as machining tolerances. It was quite a predicament because it seemed that the binding was caused by the flexing, and the flexing was caused by the binding. The other problem was mounting of the Z motor. These problems resulted in a few improvisations being made to ensure that the machine would function as expected. These improvisations will be covered shortly.

Rail Bracket and Motor Bracket

These were fabricated in the Bingham shop. The material chosen for them was aluminum. Its easy machinability with high stiffness makes it ideal for the brackets. The major design consideration was to make the brackets perfectly parallel with each other (so the rails would be parallel). Extra care was taken while machining the brackets to ensure that this. Also, the decision was made to make the brackets adjustable. This would be done by making the brackets attach to the cutting table with set screws. This accomplish two goals, firmly attaching the brackets to the table, as well as making them "float" so that they could be adjusted to ensure the parallelism of the rails.

Sliders

The HDPE sliders were machined carefully to ensure that the holes for the rails were precise as possible. This was necessary to ensure that the sliders did not bind up when the machine moved. As previously discussed, for all the care that was taken to ensure that the sliders would work they still would catch on rails. The sliders that were not on the motor side were modified. The holes where the rails would run through were slotted. The hope was that this would keep the sliders from binding, and thus keep the gantry from flexing. This by itself did not work so further adjustments were made.

Gantry Support

The gantry support was fabricated out of Aluminum. This was chosen for its rigidity. With aluminum the Y and Z axes are easily supported and do not flex. Appropriate holes were drilled for the motor to be mounted on one side.

Inserts and Z Drive Block

The inserts and Z drive blocks were made out of steel. This was chosen because it is a much harder metal than aluminum thus the threads of the interior holes will hold up better over time. The inserts were glued into the sliders and the Y block. The Z drive block was bolted to the Z axis.

Y Block

The Y block is based on the same idea as the sliders. The three pieces that composed the Y block are made of HDPE, which as its name suggests is a bit heavy. It was decided to drill holes through the Y to lighten the block, making it easier to slide on the rails. Unlike the sliders in the X direction, the Y block slides easily along the rails. Without any sort of modification needed, the Y axis moves well. The only issue was the mounting of the Z axis motor to the Y block. The motor was too lose being held by only 2 bolts, so a bracket was designed and fabricated.

Z Block

The Z block is straightforward. A simple piece of aluminum machined to the specified dimensions so that it is square on all sides. The Z block would slide in the slots cut for it in the Y block.

Improvisations

There were a few adjustments that needed to be made for the machine to work. The sliders were adjusted, by slotting the rail holes in hopes of fixing the binding. This did not work so a further adjustment was made. This adding two horizontal support rods near the base of the gantry. The intent was to keep the gantry from flexing, thus fixing the binding problem. Whether it was just the support rods, or it was the combination of the support rods and the slotting of sliders, the adjustments worked. The X axis moves steadily and is fairly repeatable.

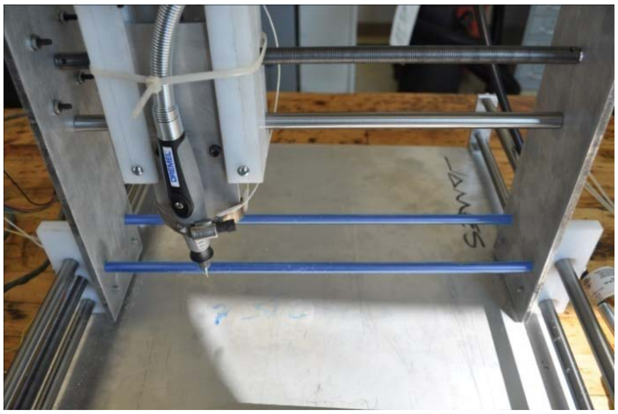

Figure 5 – Support Rods (Highlighted in Blue)

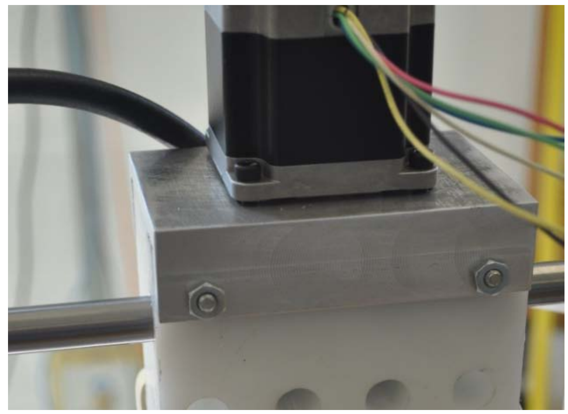

Figure 6 – Z Motor Mount

The other main improvisation was creating a motor bracket for the Z axis motor. This Y block was designed with only two holes for the motor. It was thought that this would be enough to secure the motor, but after some testing, it was not. So a small bracket was created. It was machined out of aluminum and designed to fit over the Y block as shown above.

Discussion

This design and fabrication exercise was a success strictly based on how much was learned. The process of creating a prototype from scratch is in a much better perspective now. The design process is incredibly critical to the success of the prototype. It involves so much more than what it implies. There is so much research that needs to be done before any actual design takes place. Designs also do not just start as the final product. There is an evolution of the prototype. Many revisions took place over this design. Now that a prototype has been built and tested, even more revisions could be made.

Ultimately the CNC machine works. Considering that this was designed and manufactured in under 6 months, this is pretty impressive. Slight adjustments needed to be made to the design. The revisions were well thought out even though they need to be made "on the fly". If this were a real prototype more revisions could be made, and another prototype or two could be fabricated.

Conclusions

Computer numerically controlled (CNC) mills are highly complex but for this design and fabrication exercise, they are simplified enough to make an, inexpensive CNC machine capable of holding tolerances of less than .005 inches. The feed rate of the machine is kept below 5 inches per second since the endmill in use is 1/16". With this endmill repeatable etchings in Aluminum and HDPE are possible. The maximum cut depth in aluminum is .005" while in the much softer HDPE .020" is possible. Face milling is possible in HDPE since it is so soft, but this has not been tested on Aluminum.

In the future this design can be improved. This would include finding a way to drive the other side of the X axis to ensure that it stays parallel. This can be done by adding a motor to that side, or possibly making that side belt driven. Other future improvements include a more powerful motor that is tied into the computer so that the spindle speed can be controlled, also a coolant system would be necessary if the milling done is much more than etching. The other improvements are more aesthetic.

These include creating a ventilated housing for the power supply and controller board. All in all, this was a surprising success, but there is always room for improvement.

Special Thanks

Jim Drake

R. Adam Jones

Keith Angelino

Nick Badger

Appendix

(See attached .zip file)