Milling Straight and Arced Paths

Version 3

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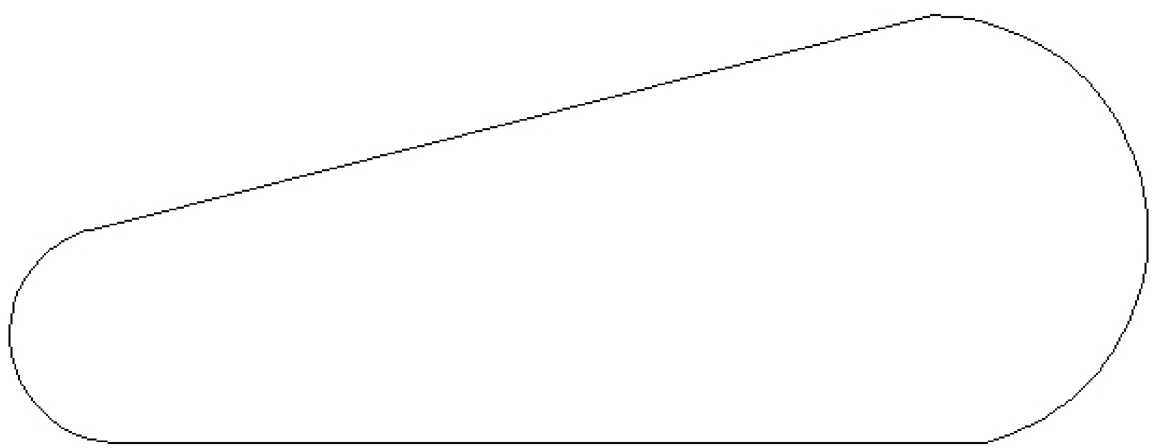
September 1, 2010

Introduction

How would you go about milling this shape?



Sure it can be done with a Computer Numerical Control mill, but what fun is that? It can also be done with a manual mill using a rotary table (RT) with an ultra-simple compound table on top.

The approach outlined here does not rely on any math. Instead, all necessary information used to cut this shape is obtained from using a Computer Assisted Design (CAD) tool.

[1] I freely give this article away but please do not modify it.

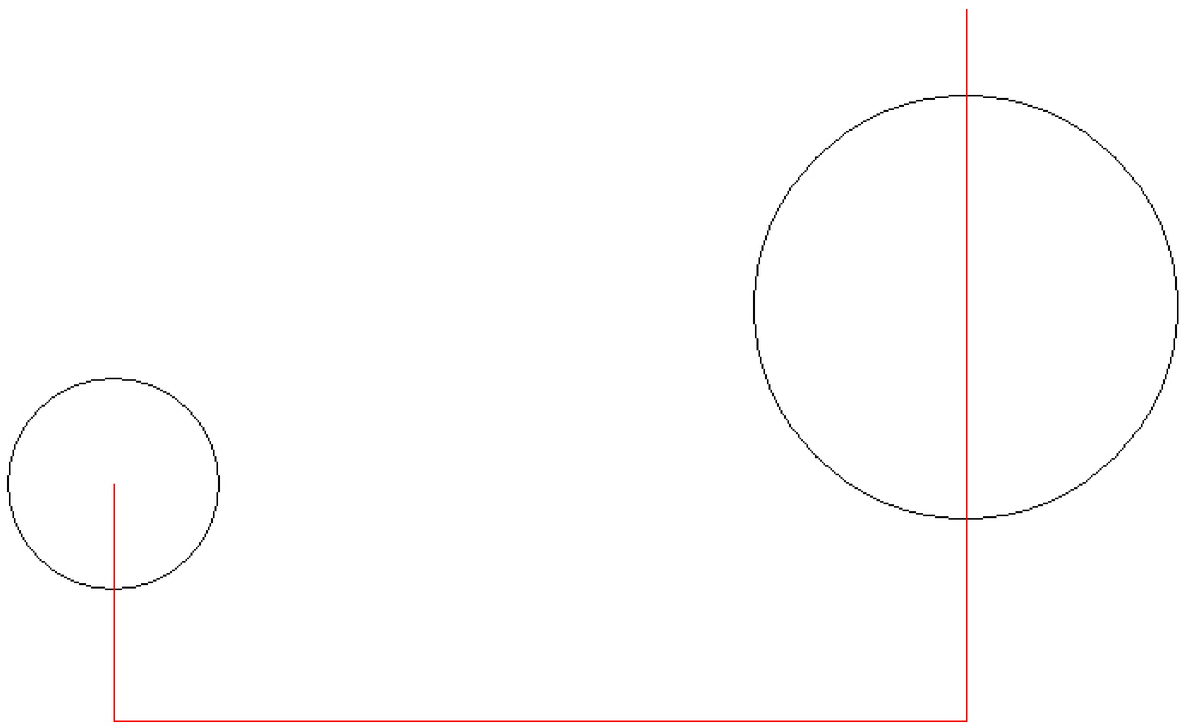
Version	Note
1	Original document as edited by Larry Gill
2	Center to center distance correction on page 3; correction in my thinking on tangent cuts on page 9; appendix added to show alternate way to draw figure
3	Explained round off error found on page 39

Contents

Drawing up the Shape

Since we will be using CAD as a geometry calculator, it is essential that the object to be cut is drawn accurately.

I am mostly self-taught so some of the following steps are probably not the best way to get the task done. I welcome readers to show me better methods. I use DesignCAD Version 14.



The small end has a radius of 0.500" and the large end has a radius of 1.000". They are separated horizontally by a center to center distance[2] of 4.000". I started by drawing a 1.000" circle on the left. A line was then drawn vertically from the center of the circle down a short distance. I then drew a 4.000" line horizontally.

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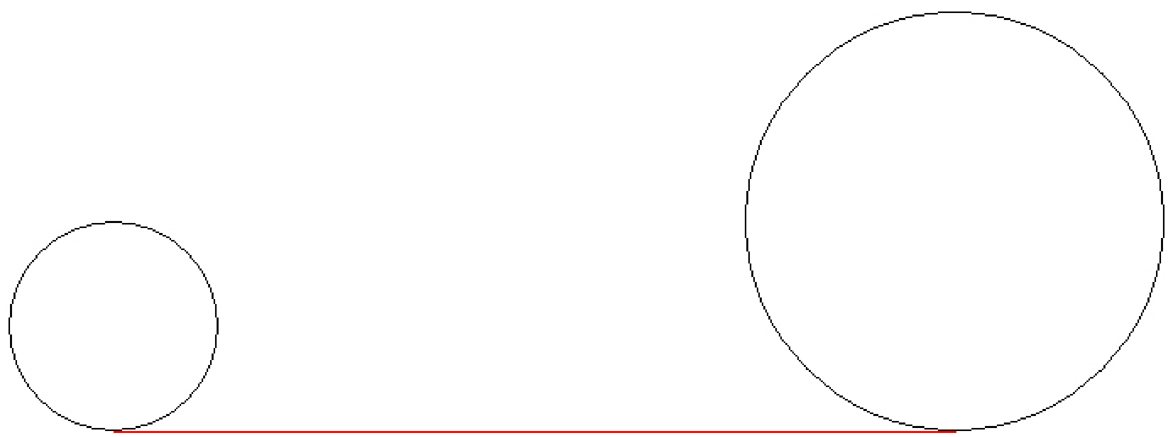
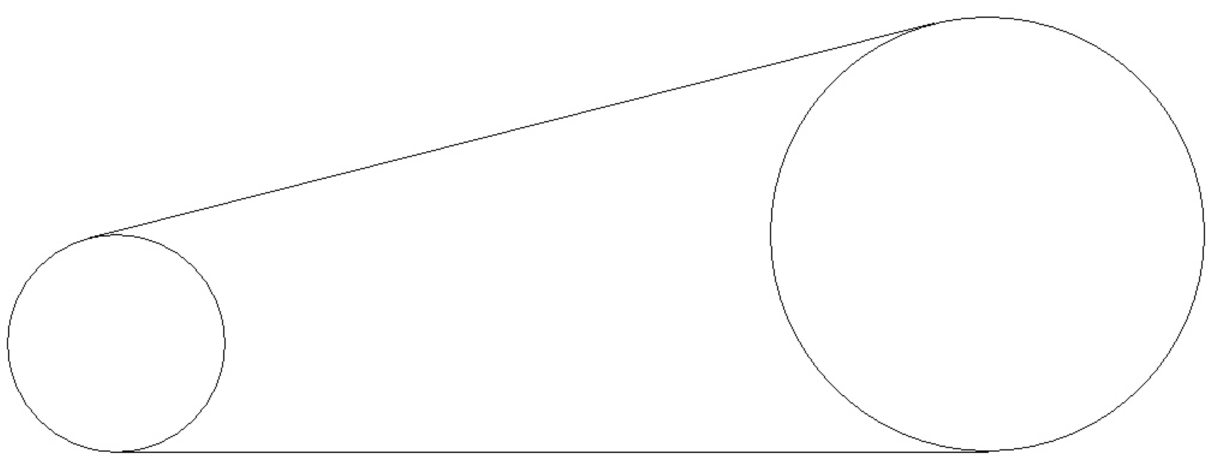
[2] I had intended to have a 4.000" center to center distance but my geometry is wrong. Along the horizontal I do have a distance of 4.000" but from center to center it is 4.031". See the appendix for the missing steps.

The left end of this line was moved so it touches the bottom end of the vertical line. I then drew a second vertical line from the right end of the 4.000” line up about 3”. Next I drew the 2.000” diameter circle. I aligned the center of this circle to the vertical line. All of this effort has put my two circles at the correct horizontal alignment.

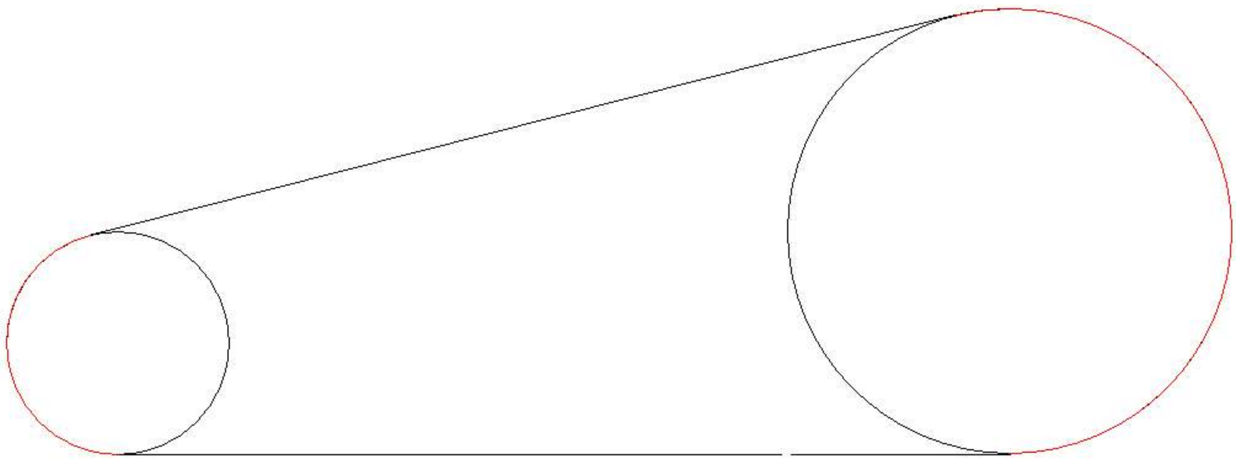
Next I want to put the two circles down on the 4.000” line. This is done by deleting the two vertical lines and doing an alignment of all objects to the bottom.



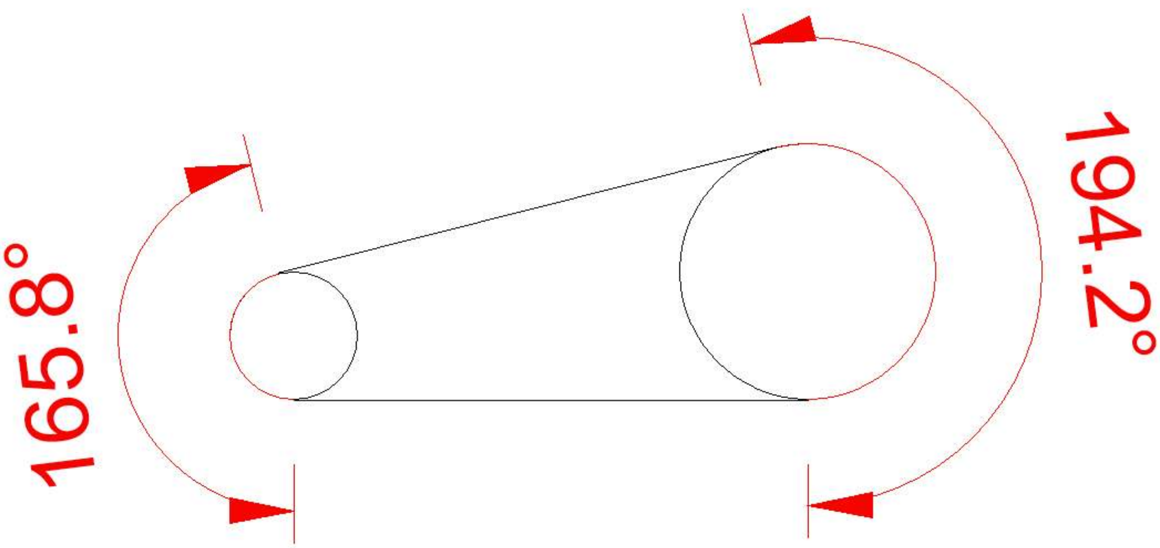
I then used the tangent tool to connect the tops of the two circles.



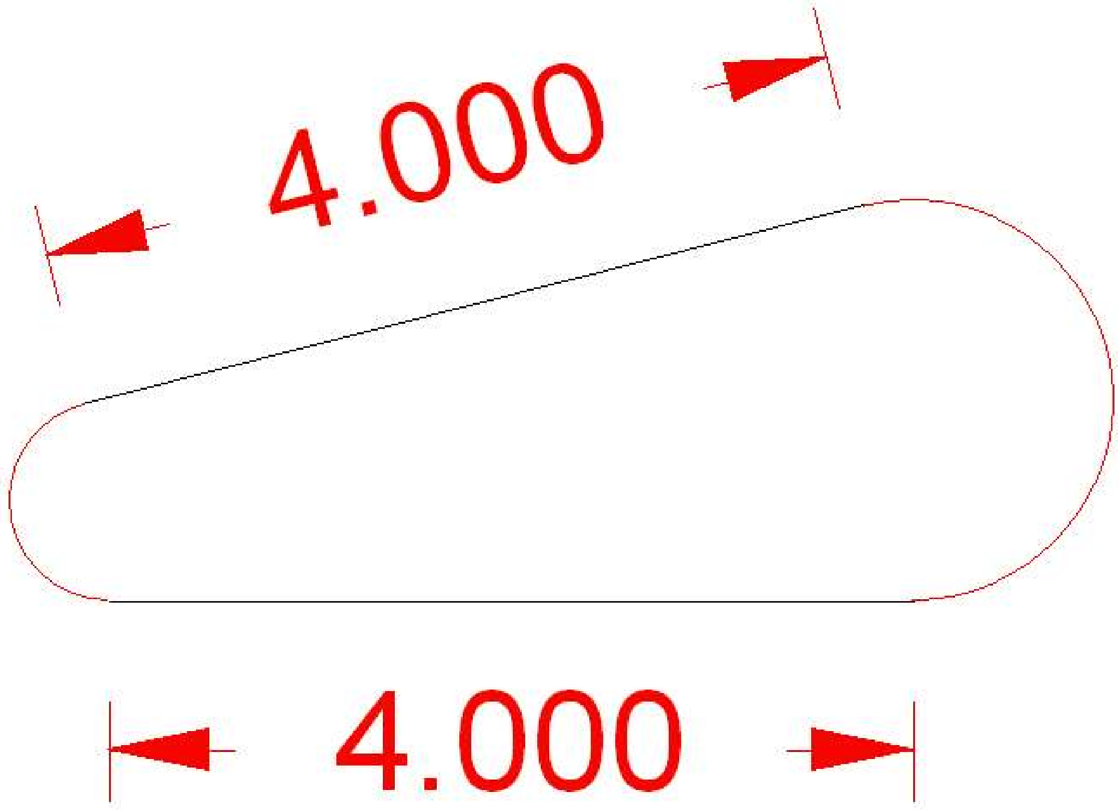
Using an arc tool, I drew the red lines which cover part of each circle. It is important to leave the circles in place for this step since the arcs need to know their centers.



Before I delete the two circles, I want to measure the number of degrees in each arc. I again use the center of each circle in order to perform this function.



I can now delete the two circles. Using the dimension tool and the fact that the ends of the arc are easily found, I measured the length of the two straight runs.



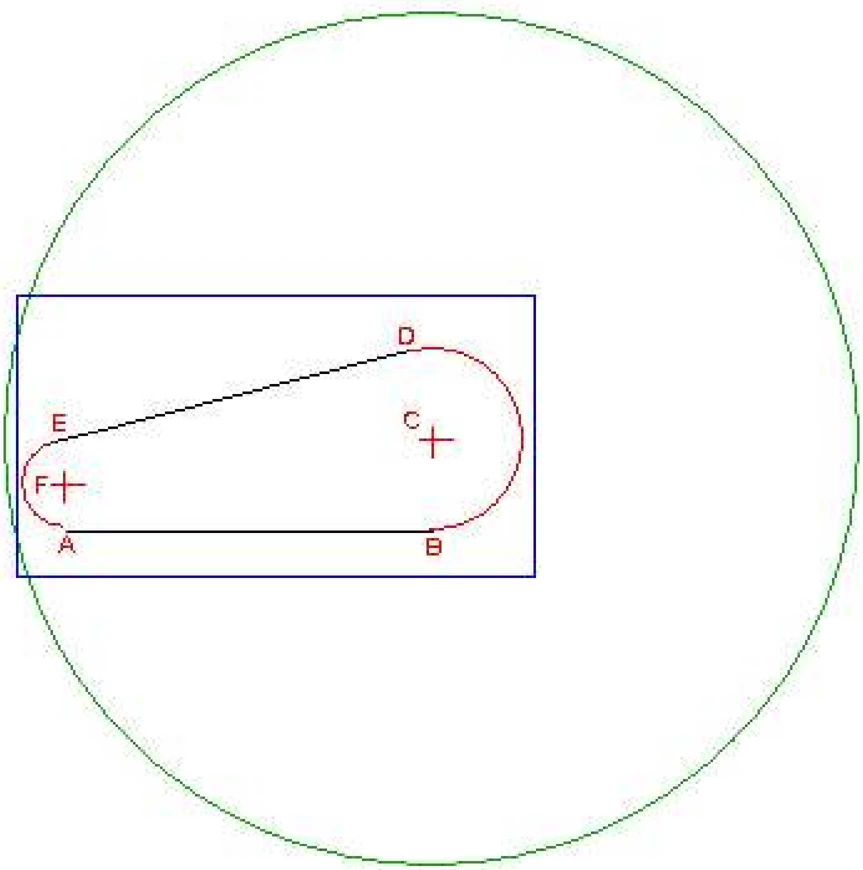
I now have all of the data necessary to cut this shape.

Shop Strategy

Rule number 1: only use procedures that require moving one axis or angle at a time. Doing more than that puts you into the realm of Manual Numeric Control. That is an entirely different can of worms.

Rule number 2: in planning how to cut the shape, keep in mind what needs to be done next.

I don't want to get into tool offset at this time so let's deal only with tool path. The center of our end mill will follow the line.

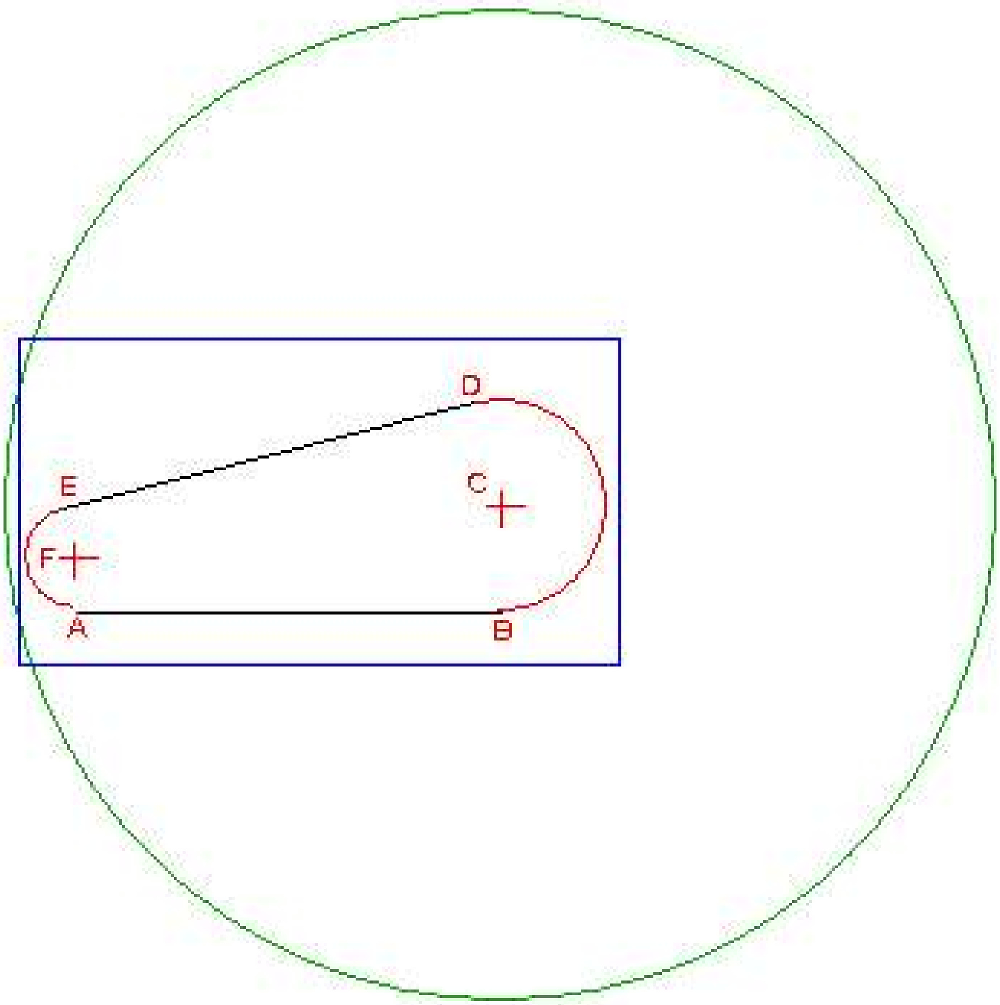


Let's use our design as an example of this rule and an overview of what is ahead.

By starting at point "A", I need to move to point "B". To do this, line A-B must be aligned with either the X or Y axis of the mill. I choose the X axis. Once at point "B", I need to cut an arc. Why not start out with the center of the arc, point "C", at the center of the RT. I can then just get to point B and crank the RT through the B-D arc. When I get to point "D", line D-E will be parallel to the X axis so I just crank the X axis feed and can cut line D-E. Things get a bit tricky with the cutting of arc A-E. I must move the part such that my center of rotation is at point "F" and my cutter is at point “A” or “E”. It is easiest to find point “A”. After the part has been repositioned and the cutter placed back at point “A”, the RT is again cranked to cut arc A-E.

As you can see, it is far better to plan this out before starting the cut than to wing it half way through.

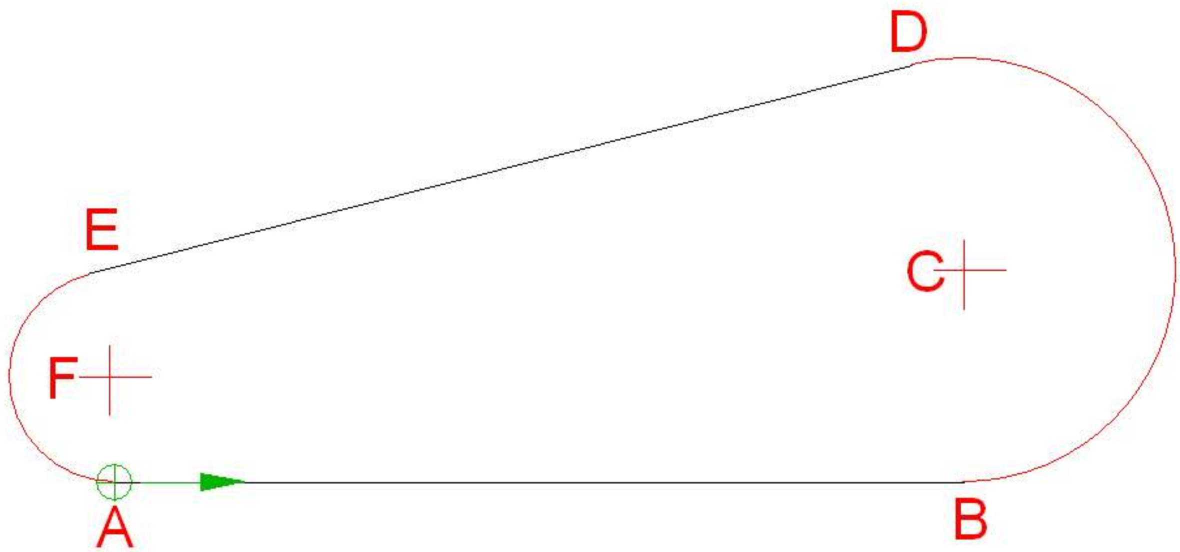
Detailed Planning of the Cut



The block to be cut, shown in blue, is set up on the RT so line A-B is parallel to the mill’s X axis and point C is at the center of rotation of the RT. The (0,0) point of the mill table is set up at the center of rotation of the RT.

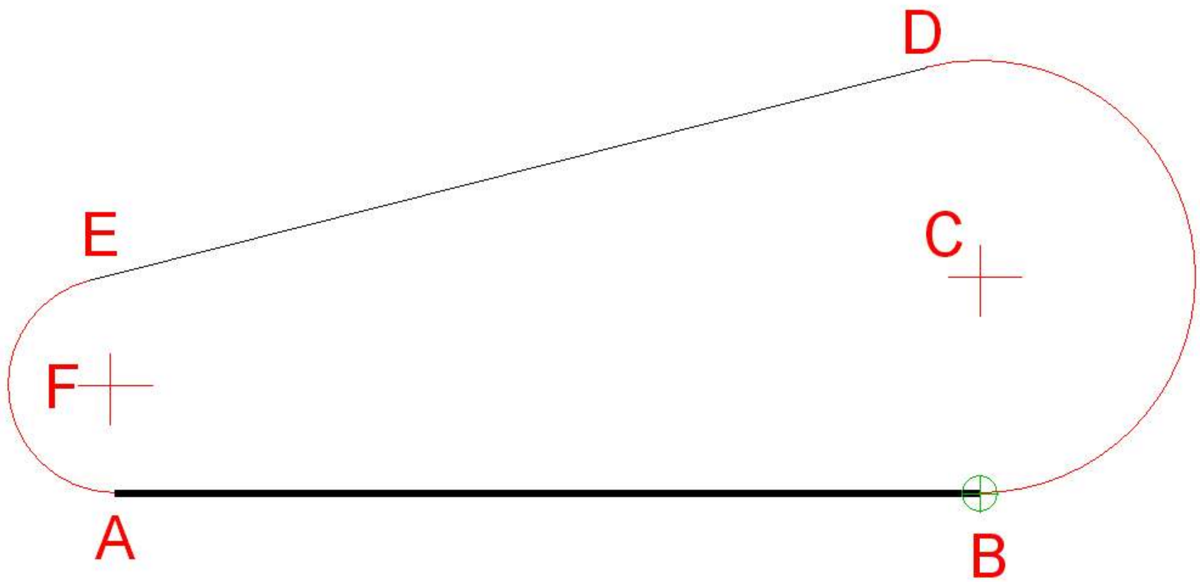
Note that as we turn the RT, all cuts along the X axis will be tangents of the arc B-D.

I will leave the outline of the block out of subsequent pictures.

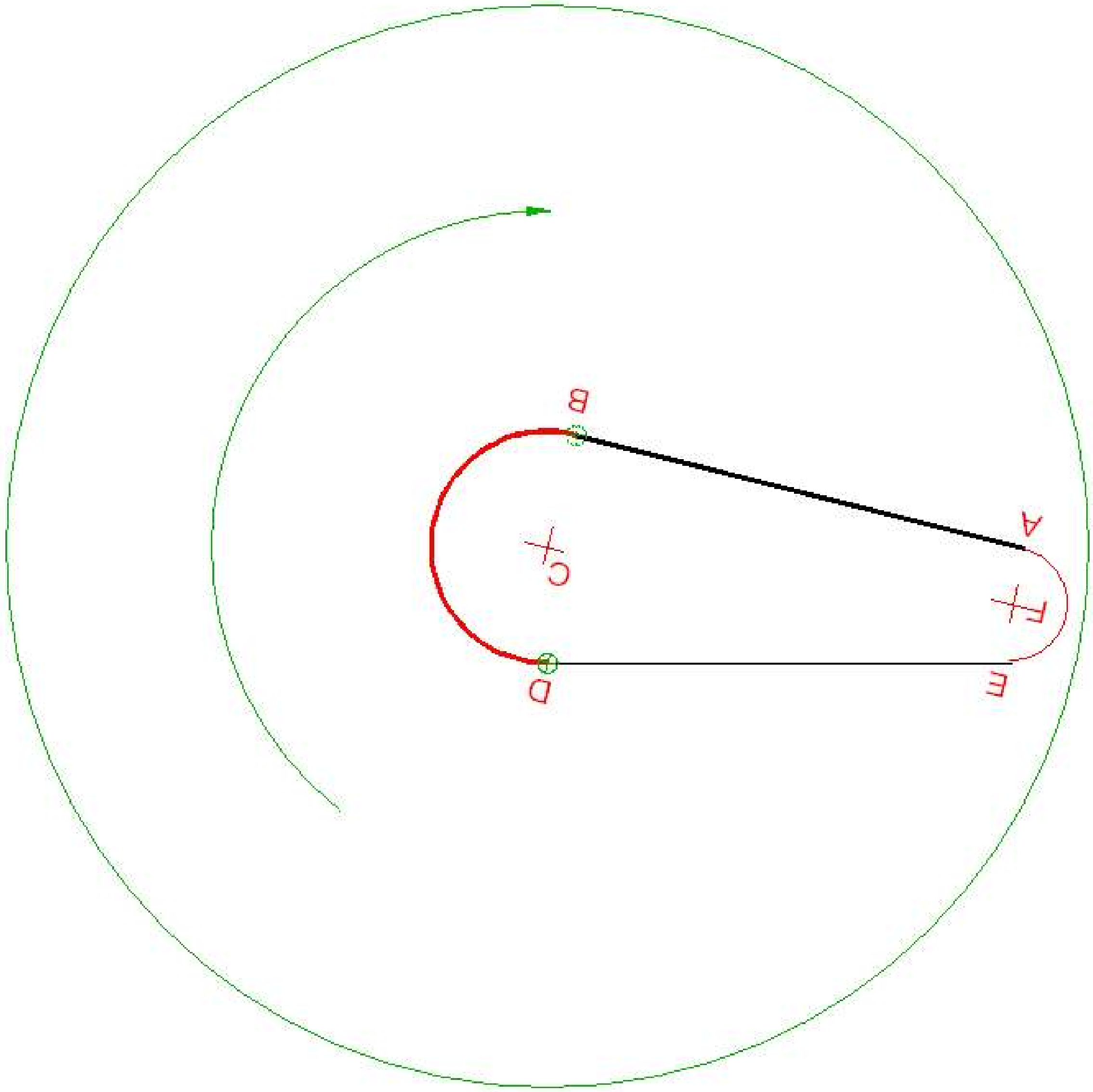


I want to move my cutter to point A. This entails moving the Y axis so the cutter is at point B, a distance equal to the radius of the large circle. I then move along the X axis until I get to point A.

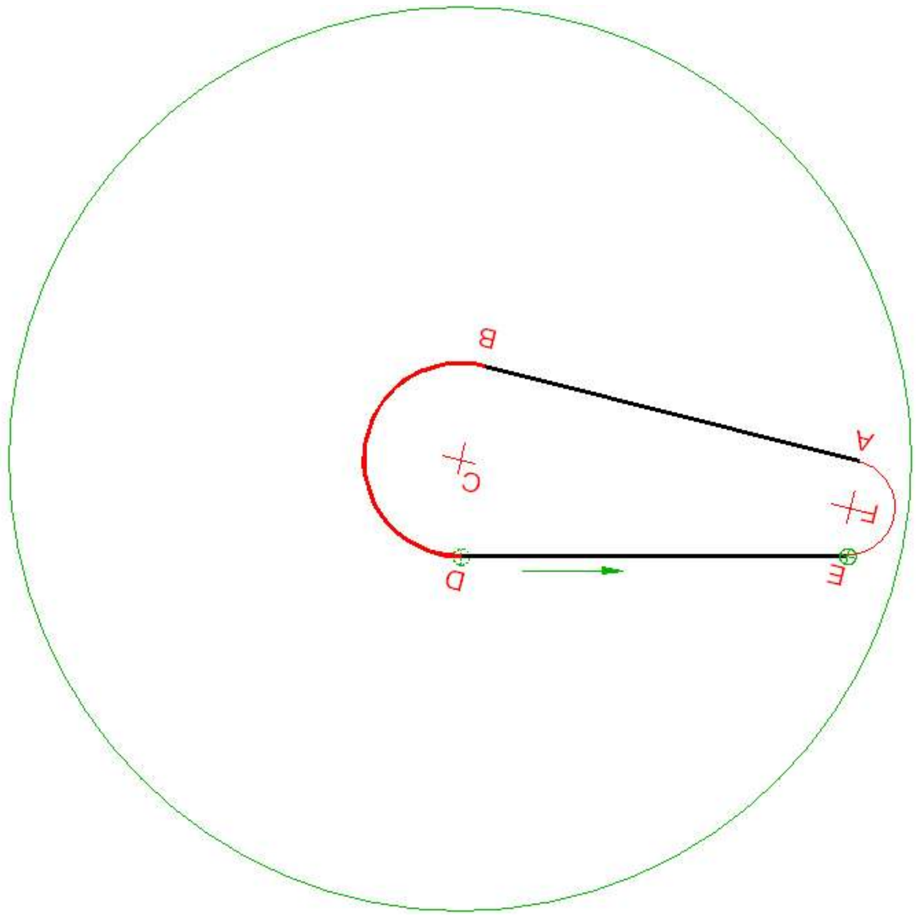
So it was a 1.000” move down and a 4.000” move over. Lock the Y axis and the RT. We can now start our cut at “A” and move to the right 4.000” to point B.



Now we lock the X axis and unlock the RT.

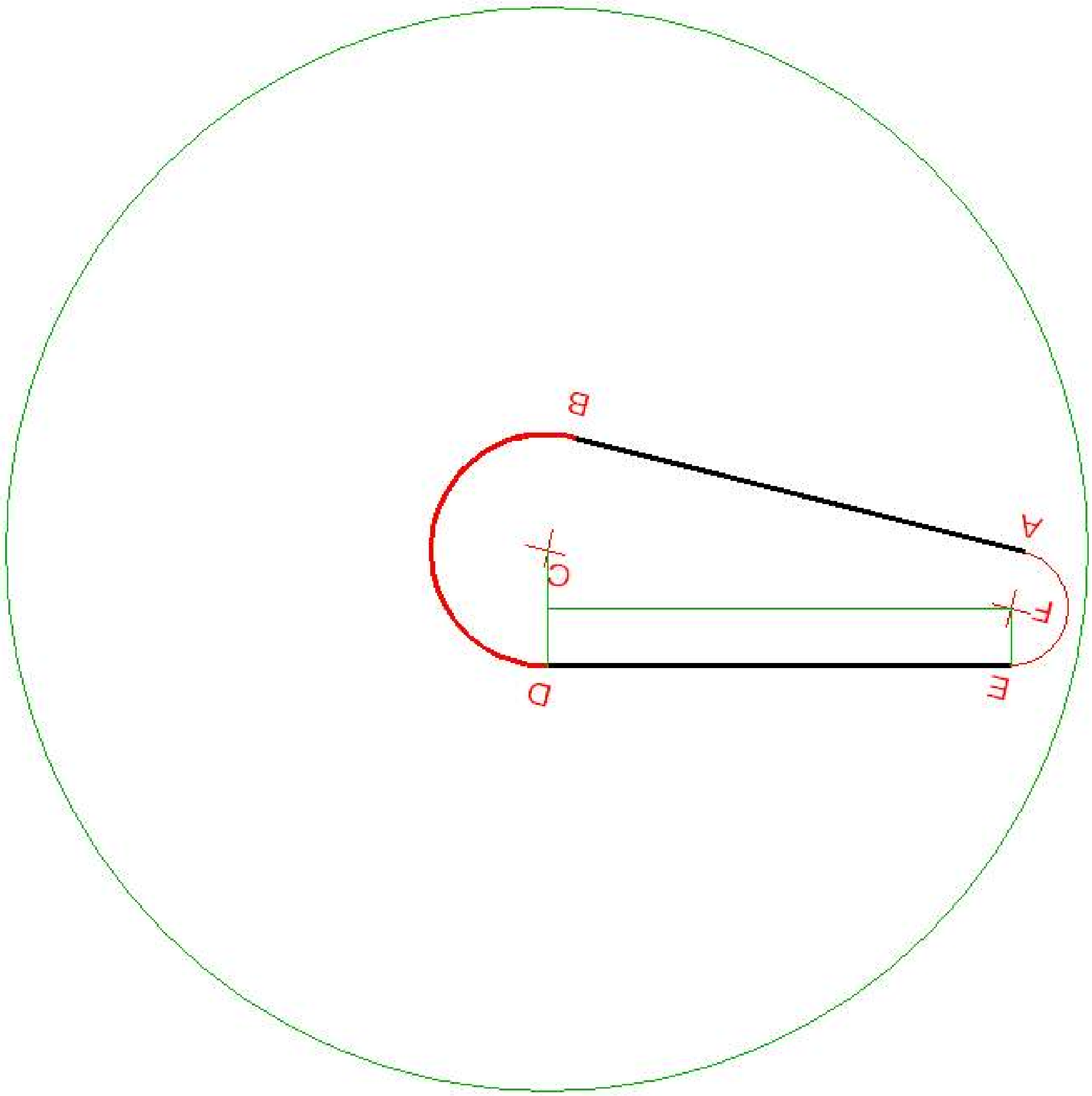


By cranking the RT 194.2º, we trace the arc and end up at point D. Note that the cutter went from point B to point D because the RT turned clockwise. It may seem strange but remember that the cutter really does not move, the part moves.

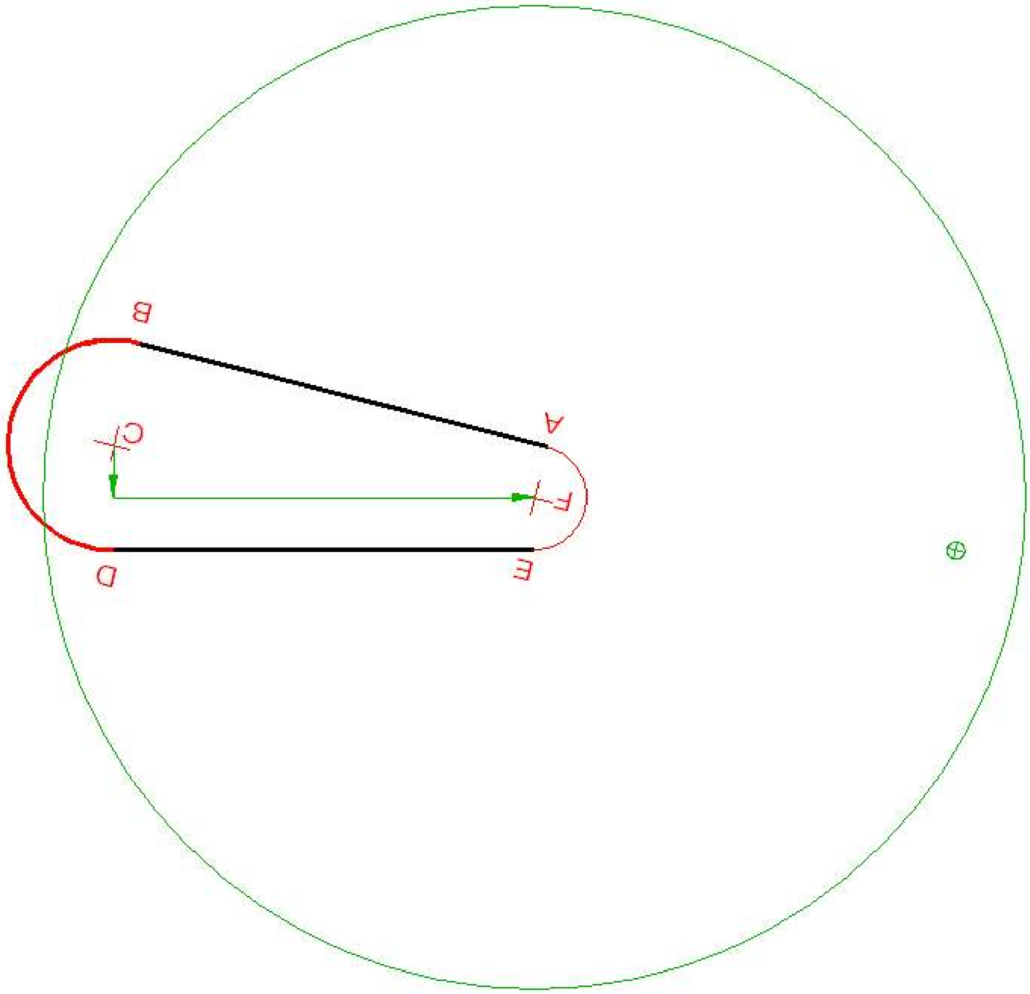


Line D-E, a tangent of the B-D arc, is parallel to the X axis as discussed on page tangents9. We just have to lock the RT, unlock the X axis, and move the cutter along line D-E to point E. At point E, the cutter is raised from the part.

When we were at point B, it was a simple matter of turning the RT in order to cut arc B-D. That was because point C was set up as the center of rotation. But now we are ready to cut arc E-A with its center of rotation at point F. If we just rotated the table again, arc E-A would be centered at point C and give us an arc with a radius of about 4” and not the 0.500” radius called for in the design.

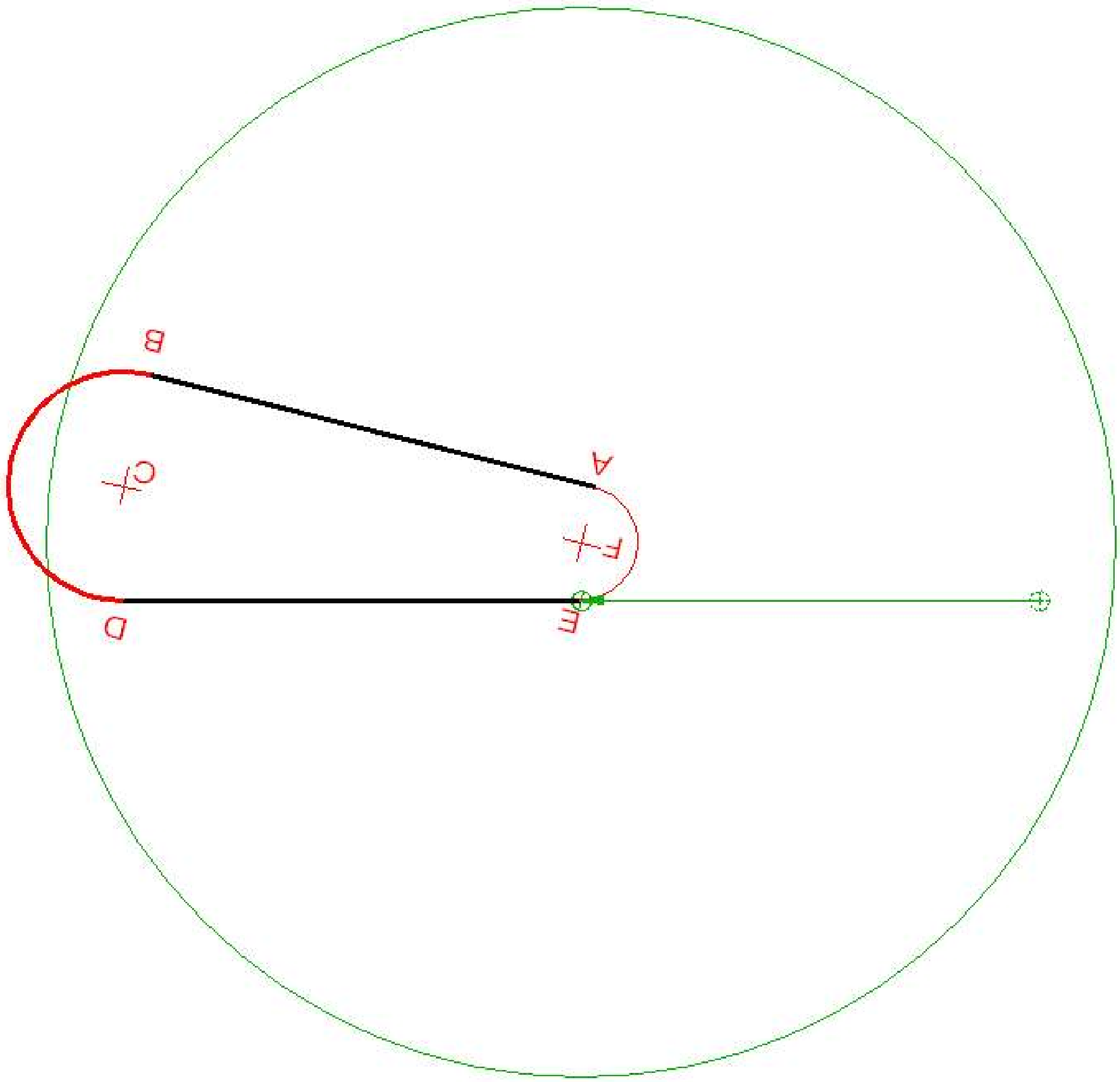


We must move our **part** so the center of rotation is at F. It has been at point C. Note that along the X axis, these two points are at a distance equal to line D-E which we know to be 4.000”. Along the Y axis we know that point C is the large radius above line D-E. Point F is the small radius above line D-E. This tells us that point C is 1.000” – 0.500” = 0.500” above point F. So to get the center of rotation moved from point C to point F we must slide the part to the left 4.000” and then up 0.500”. For now, assume I have a way to accurately do this move.

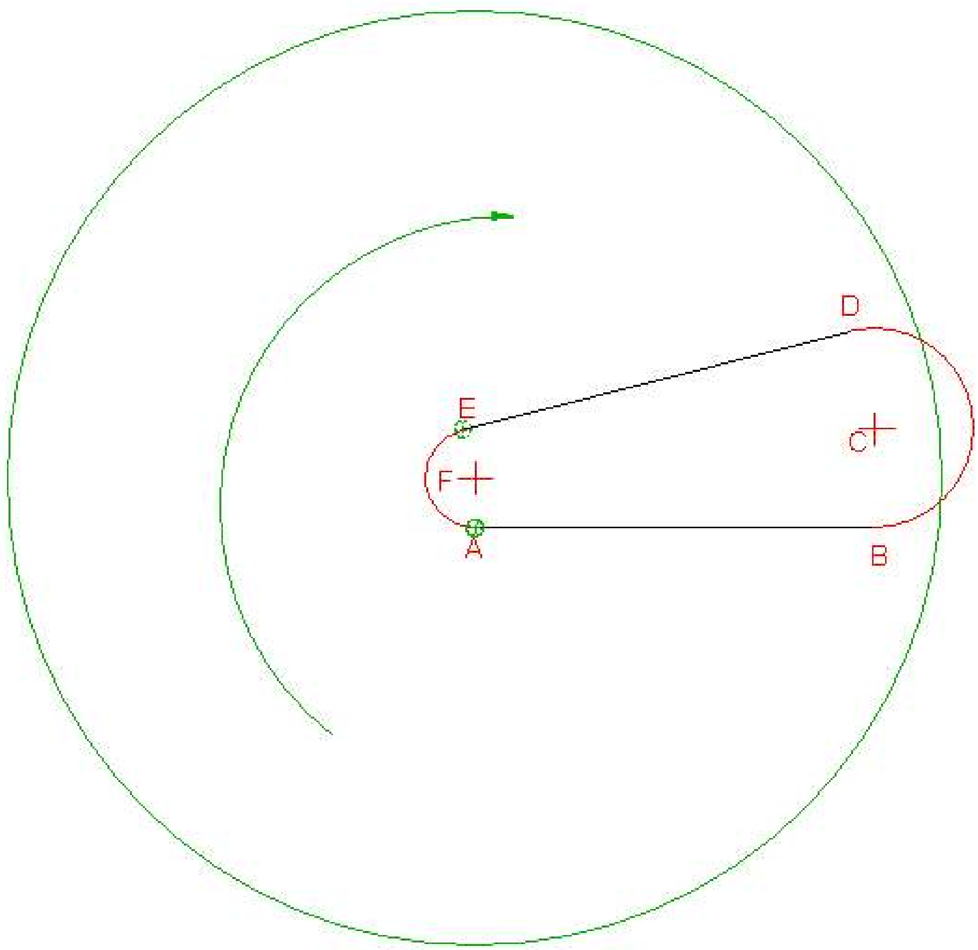


We have moved the center of rotation down and to the right which means that we have moved the part up and to the left.

Note that the cutter has not moved yet. It must be moved back to point E.



We know that point F is at (0,0) because that is how we initially set up the RT. Point E is directly below point F at a distance equal to the radius of the E-A arc, 0.500”. By moving the mill’s XY table, we put the cutter at point E. It is now lowered back into the part in preparation for cutting arc E-A.



The X axis is locked and the mill started. Our part is rotated about point F clockwise. This causes the cutter to move from point E to point A and cut the 0.500" radius arc. The part is now finished.

But wait one minute. How did we shift the part so the center of rotation changed from point C to F? It is time to tell the rest of the story.

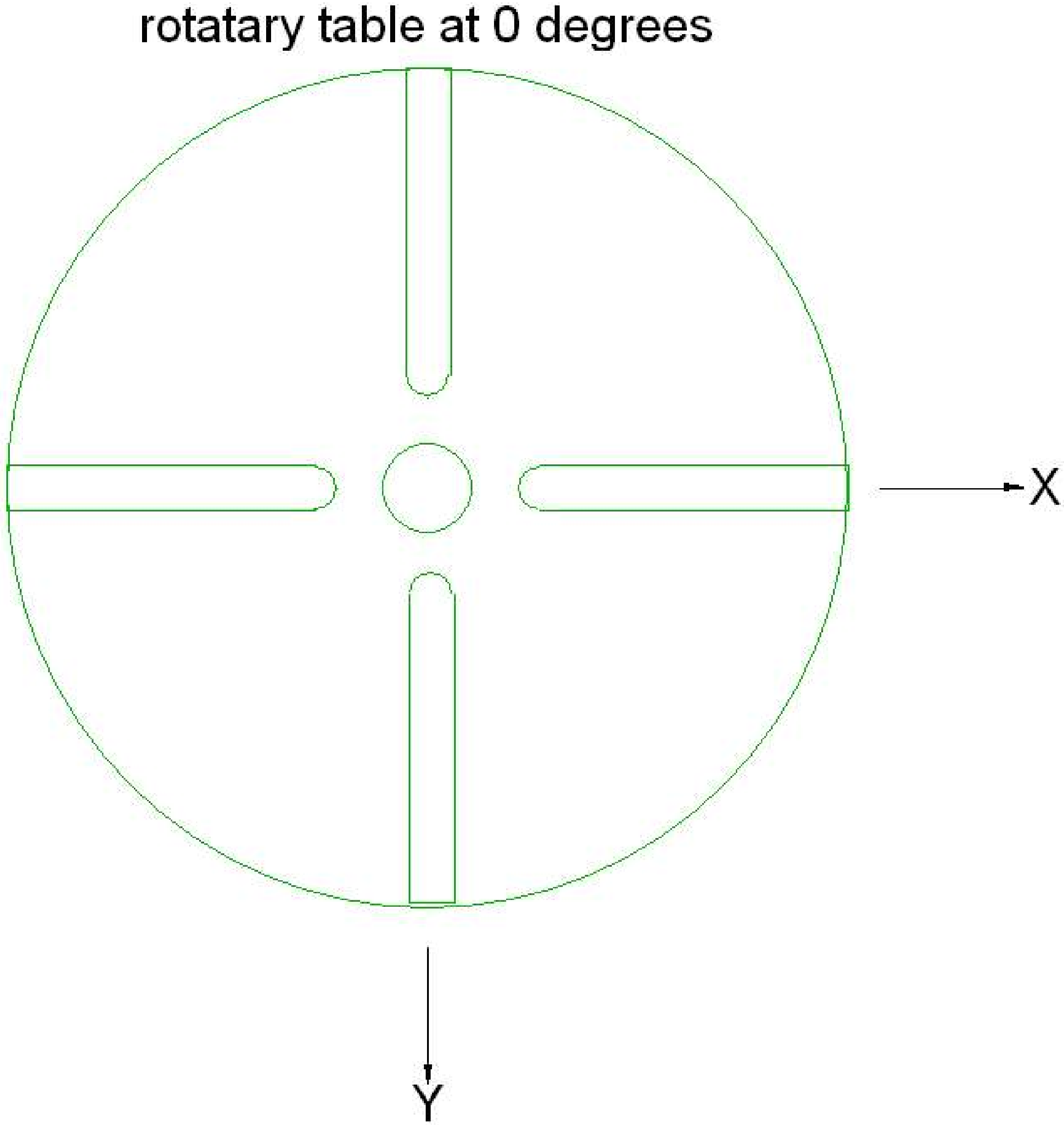
The Compound Function

The standard means of moving the center of rotation of a part mounted to a RT is to use a compound. This is a small XY table that is supported by the RT and in turn supports the part being cut. As a hobbyist, I have two problems with the compound. First of all, given how often I plan to use it, the cost is high. A decent compound goes for around $100. The second and more troubling problem relates to height. I own a mill/drill. When I put my RT on the mill table, I lose about 4” of headroom. If I then put a compound on top of the RT, I will lose another 3 to 4”. There isn’t much left for the part, a drill chuck, and a drill.

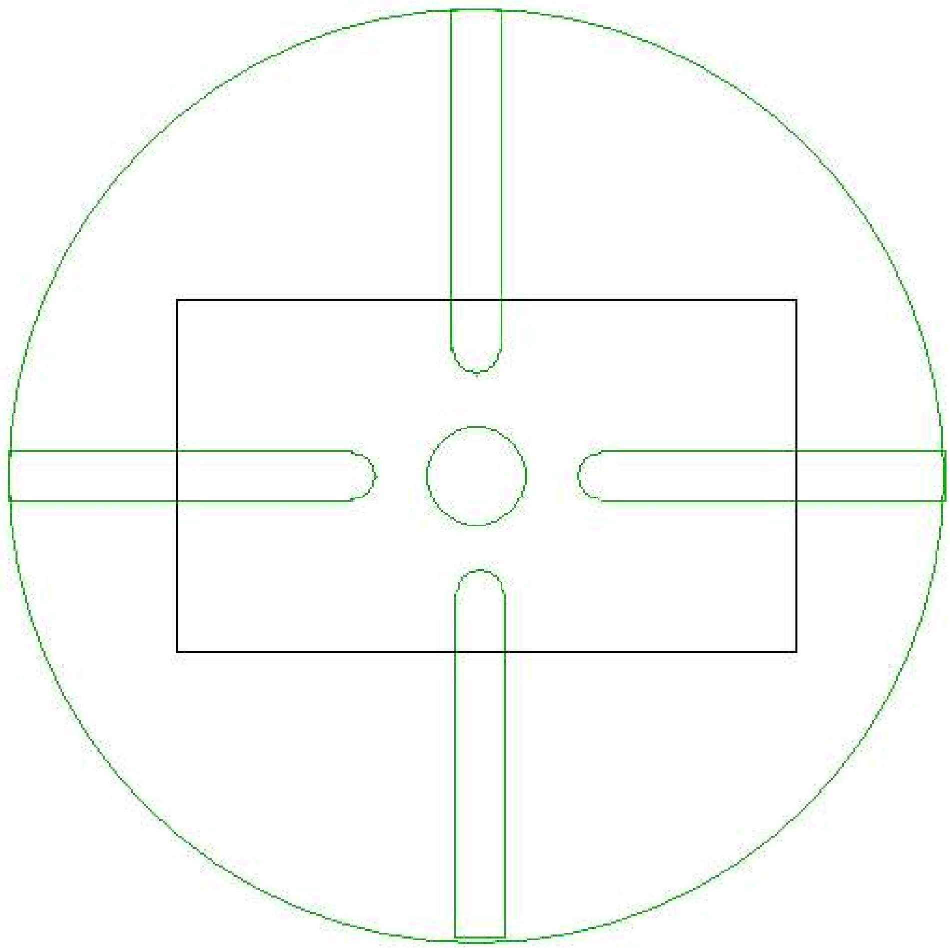
It is time to get sneaky. Note in the example that I did not cut the part while I shifted the center of rotation. This means that the compound’s ways and lead screws do not have to be strong. In fact, I don’t need any as you will soon find out.

A Minimalist's Compound

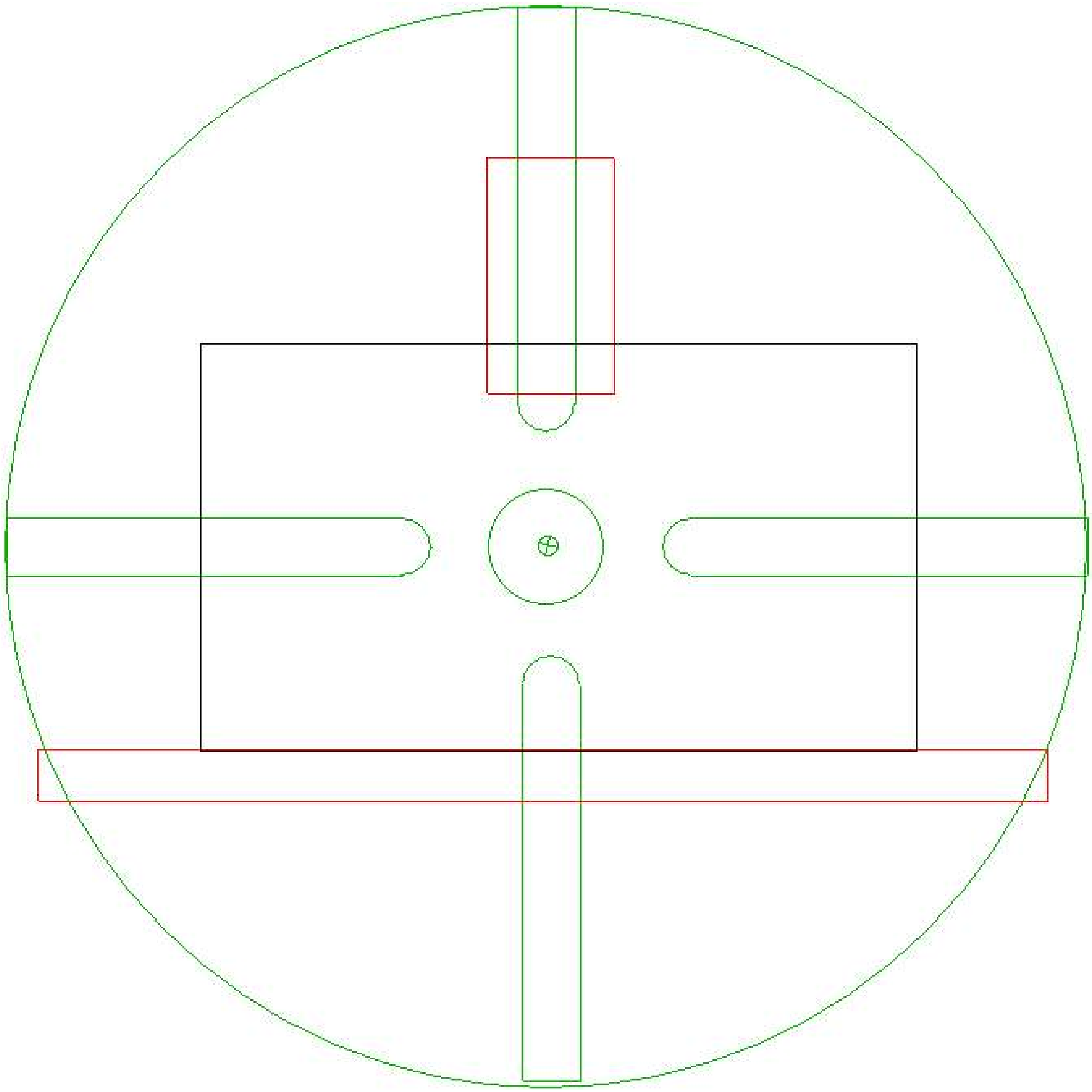
Let's take a closer look at my RT first.



My RT is set at 0º. The center of rotation is aligned with the center of rotation of the mill's spindle. This puts my (0,0) point at the center of the RT. Note that I choose to define my positive X direction to the right and my positive Y direction to the front as the table is viewed from the top.

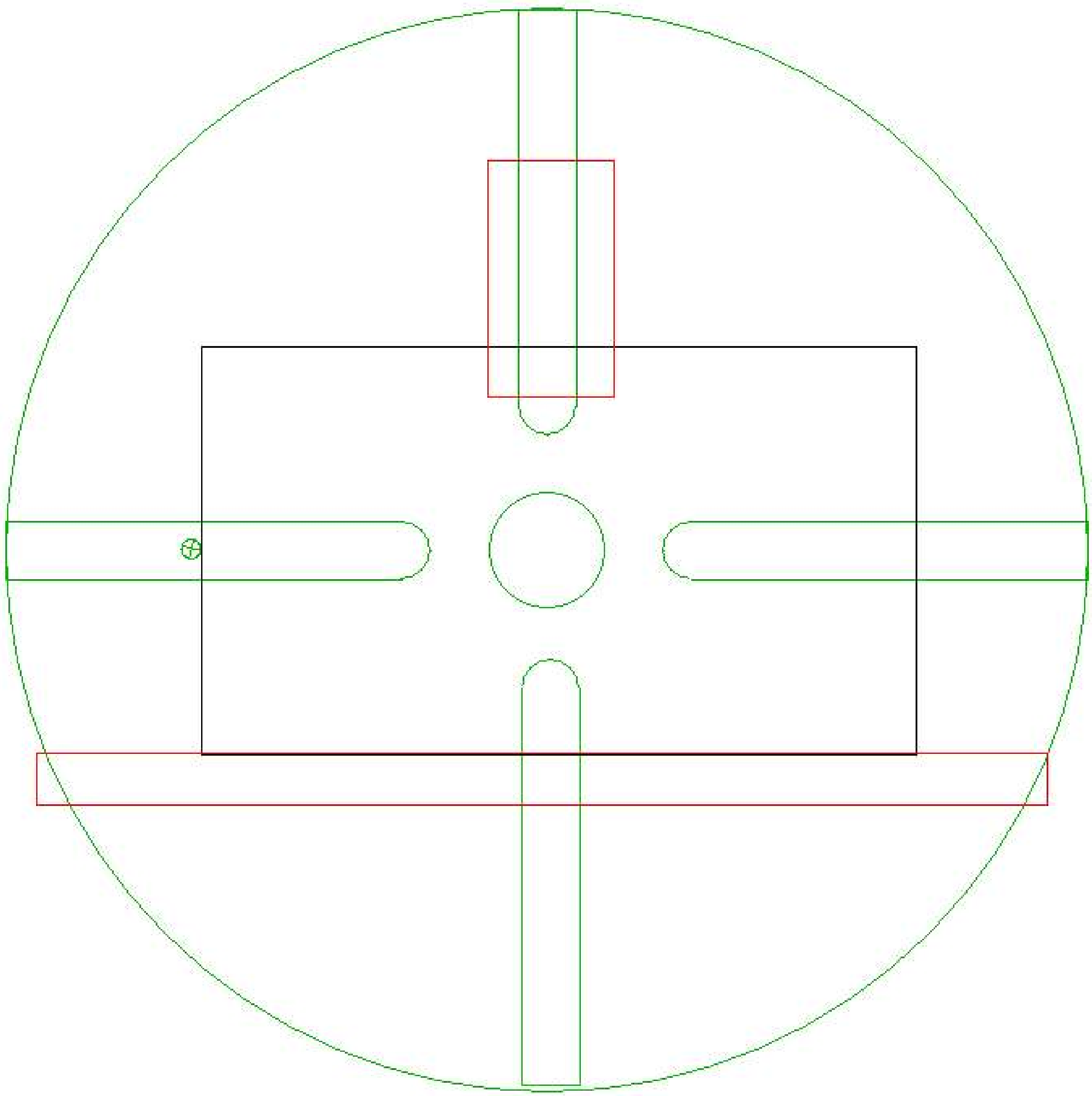


Say I place a machined square ½” thick plate of 6011 aluminum on top of the RT.



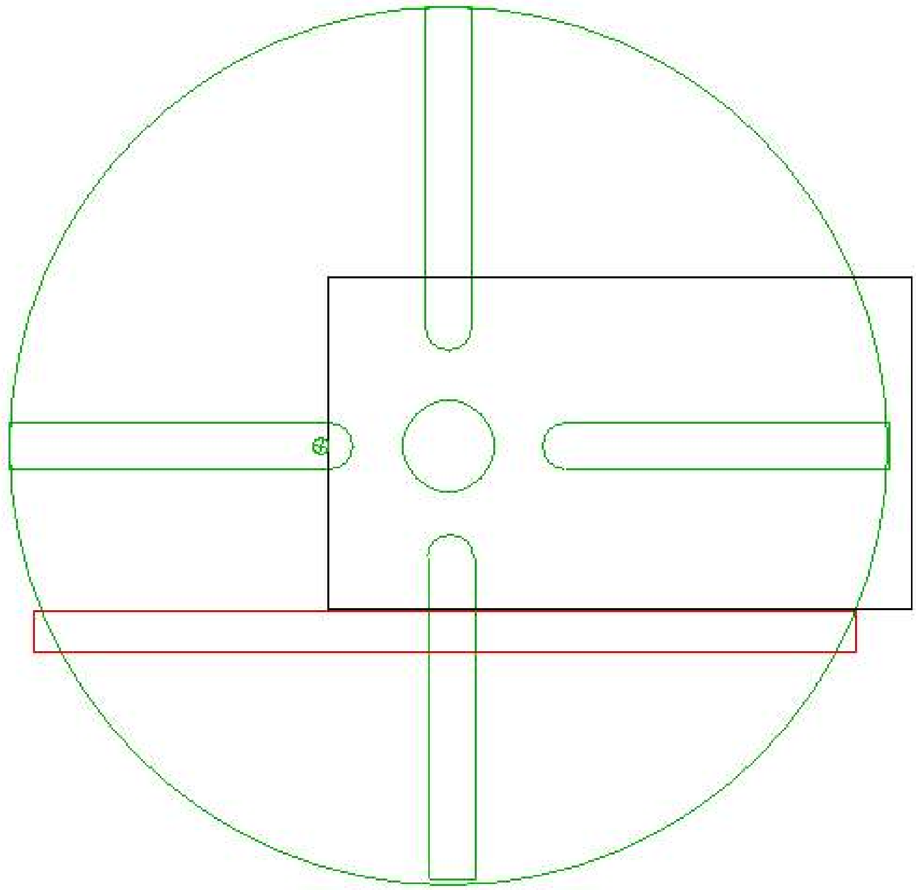
I don't want it to move yet so add a clamp at the 12:00 position. I also add a fence along the bottom[3]. Assume that the fence is clamped in place and aligned with the X axis. The center of rotation of the mill's spindle is marked with a small circle with a cross inside.

[3] It should go without saying that before you add any alignment tool, all surfaces must be free of swarf.

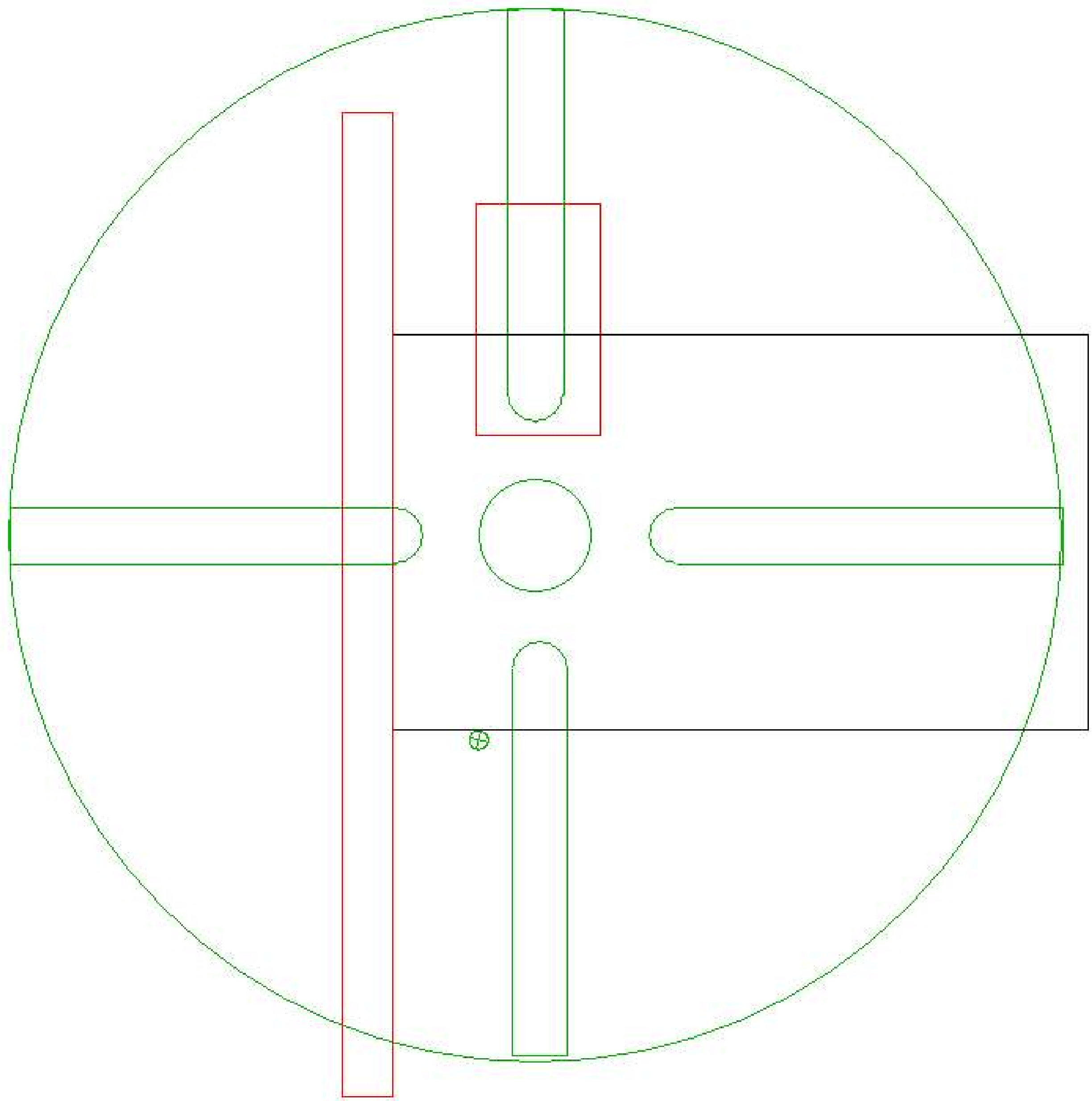


I have now moved the mill table along the X axis such that my spindle center of rotation is at the left side of the plate. Additionally, A small but rigid rod has been fitted into the spindle. The rod is in contact with the plate.

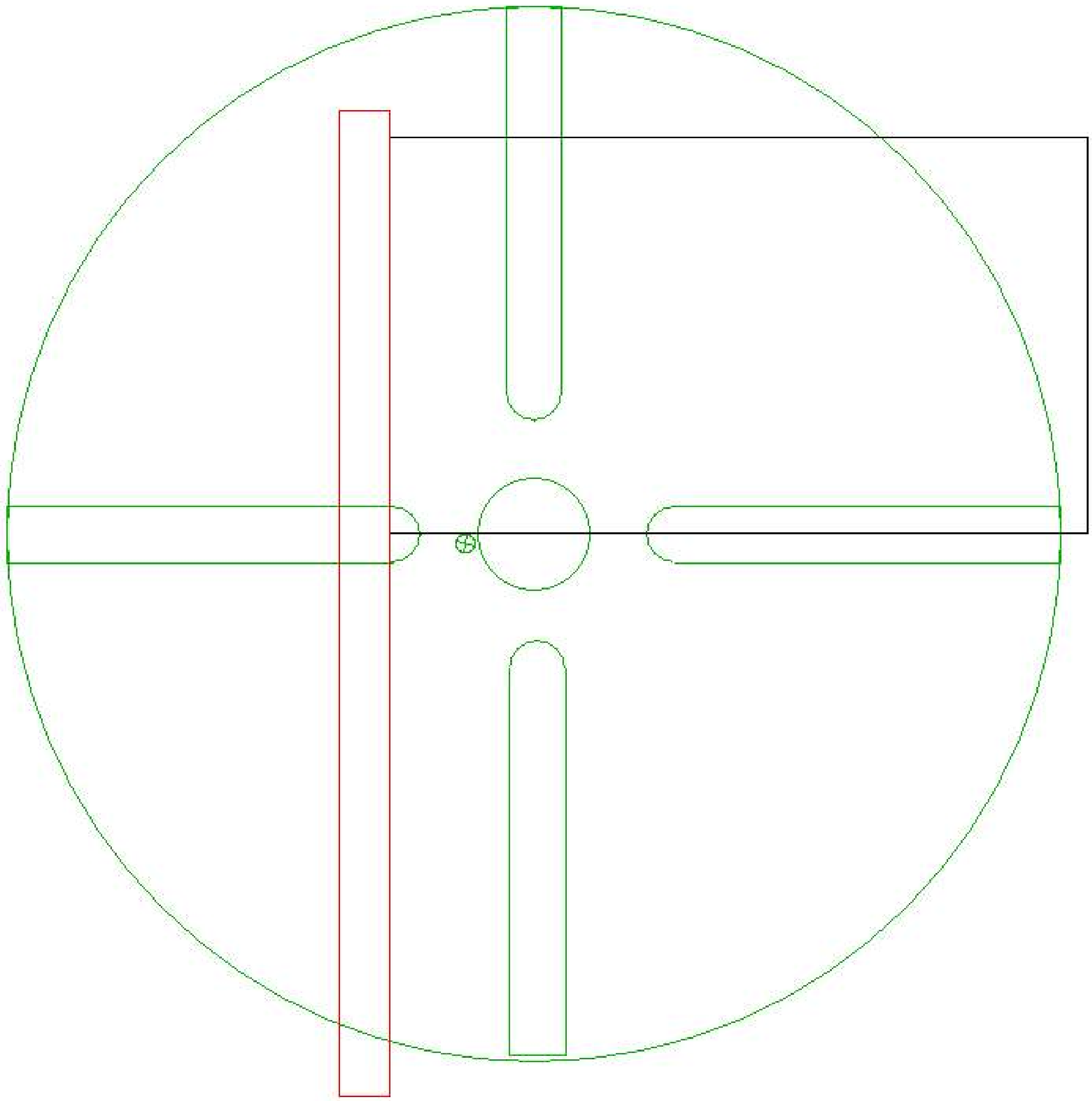
Next, I remove the clamp holding the plate. I don't lose position because the fence prevents it from moving in the positive Y direction and my rod prevents it moving in the negative X direction.



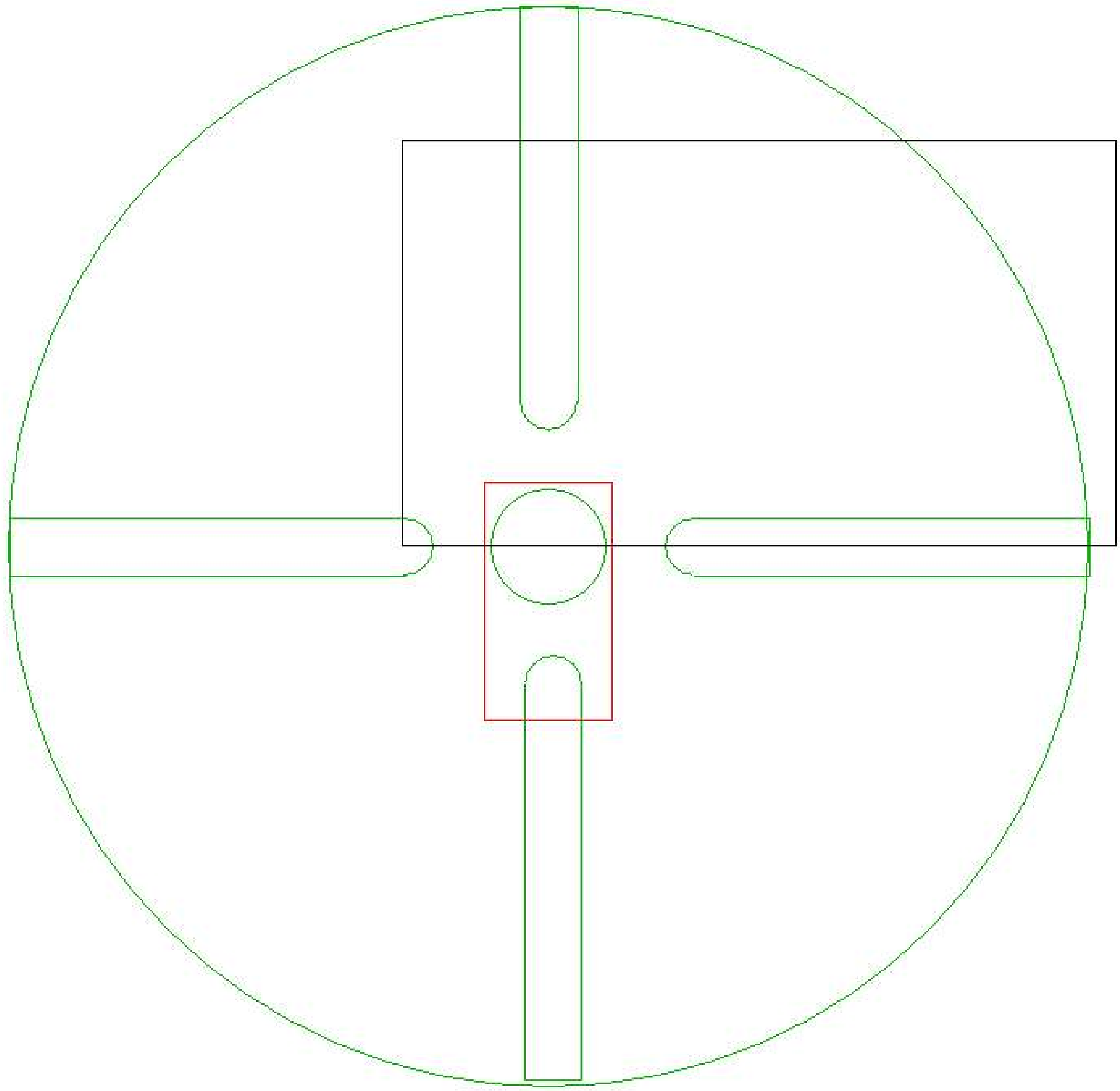
By moving the mill table to the left, my spindle mounted rod pushes the plate to the right. The fence insures that no motion along the Y axis will take place. Since no cutting is going on here, a light touch on the plate keeps it in contact with both the rod and fence. I know exactly how much the plate has moved because I can read it off of my mill table's X axis position indicator.



I first put back the clamp so the plate can’t move. Then I move the fence so it is now contacting the left side of the plate. My rod is now touching the front side of the plate near the left corner.



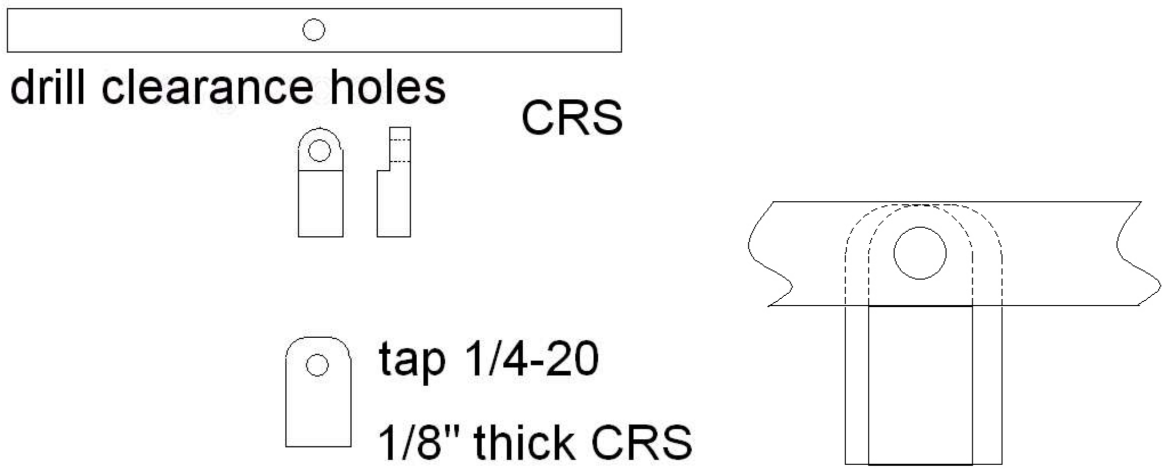
By moving the mill table in the positive Y direction, the spindle mounted rod is pushing the plate in the negative Y direction along the fence. As with the X direction, I can use the Y axis indictor to tell me how far I have moved the plate.



The clamp has been reapplied and the fence removed. My plate has been reposition on the RT using a fence, a clamp, a spindle mounted rod, and the accuracy of the mill table's XY positioning function. This process is a lot more bother than just using a compound mounted to the top of the RT but has the advantage of very low cost and low height. Given how many times I expect to need this function, I will gladly put up with the extra steps.

The Fence

The fence uses a T slot on the RT to lock in its position. Alignment is best done with a machinist square referenced to the base of the RT.



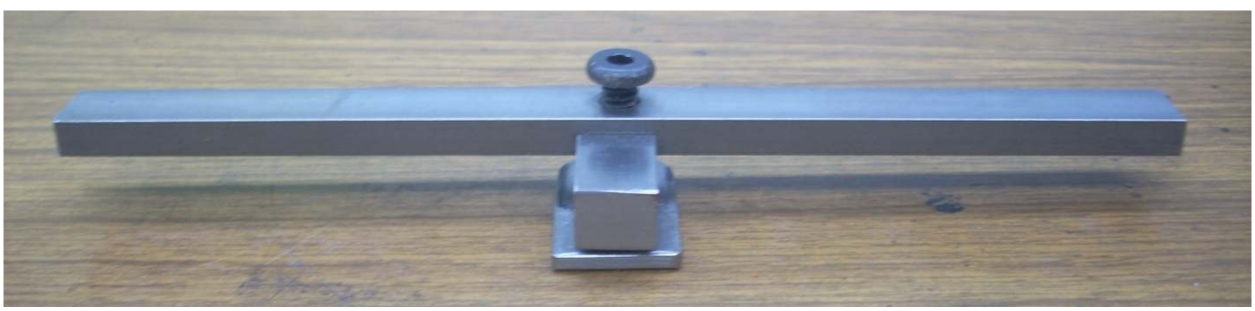
The dimensions of the various parts must come from your RT. The assembly is held together with a socket head ¼-20 screw. No need to tighten a lot since the goal here is just to prevent the fence from moving as we reposition the plate. The rounded part with the cut out was initially supposed to give me alignment to the T slot but it is too sloppy. You may wish to just make the bar and tapped part that engages the T slot.

This should all be made clear in the next section where I try out this procedure and new tool in my shop.

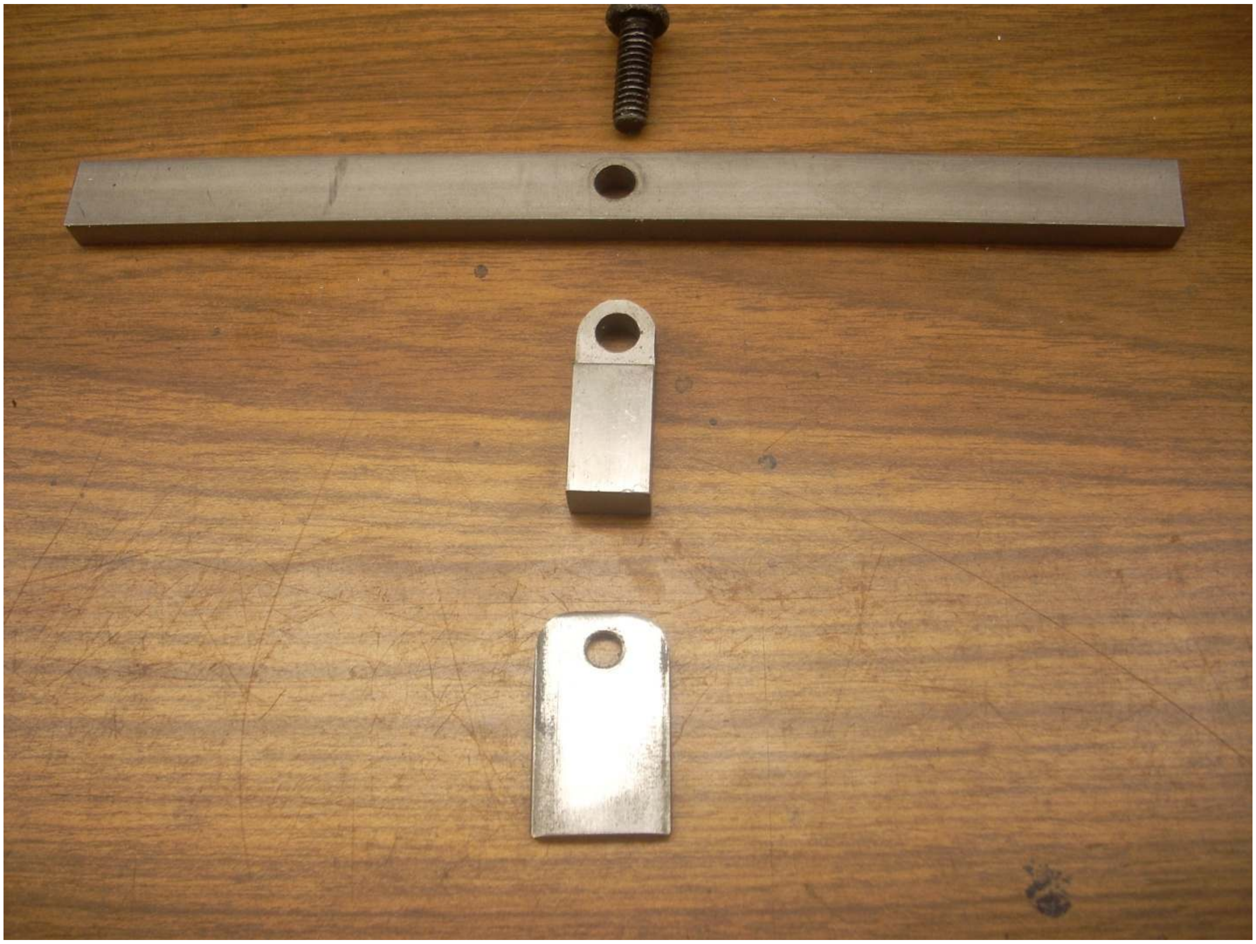
Shop Work

Custom Tools

The first thing I made was the compound. It consists of a plate of 6011 aluminum with a grid of ¼-20 tapped holes in it. The plate has been machined square and is about ½” x 3” x 6”. I’m sure this will be handy in the future but I didn’t use it this time.



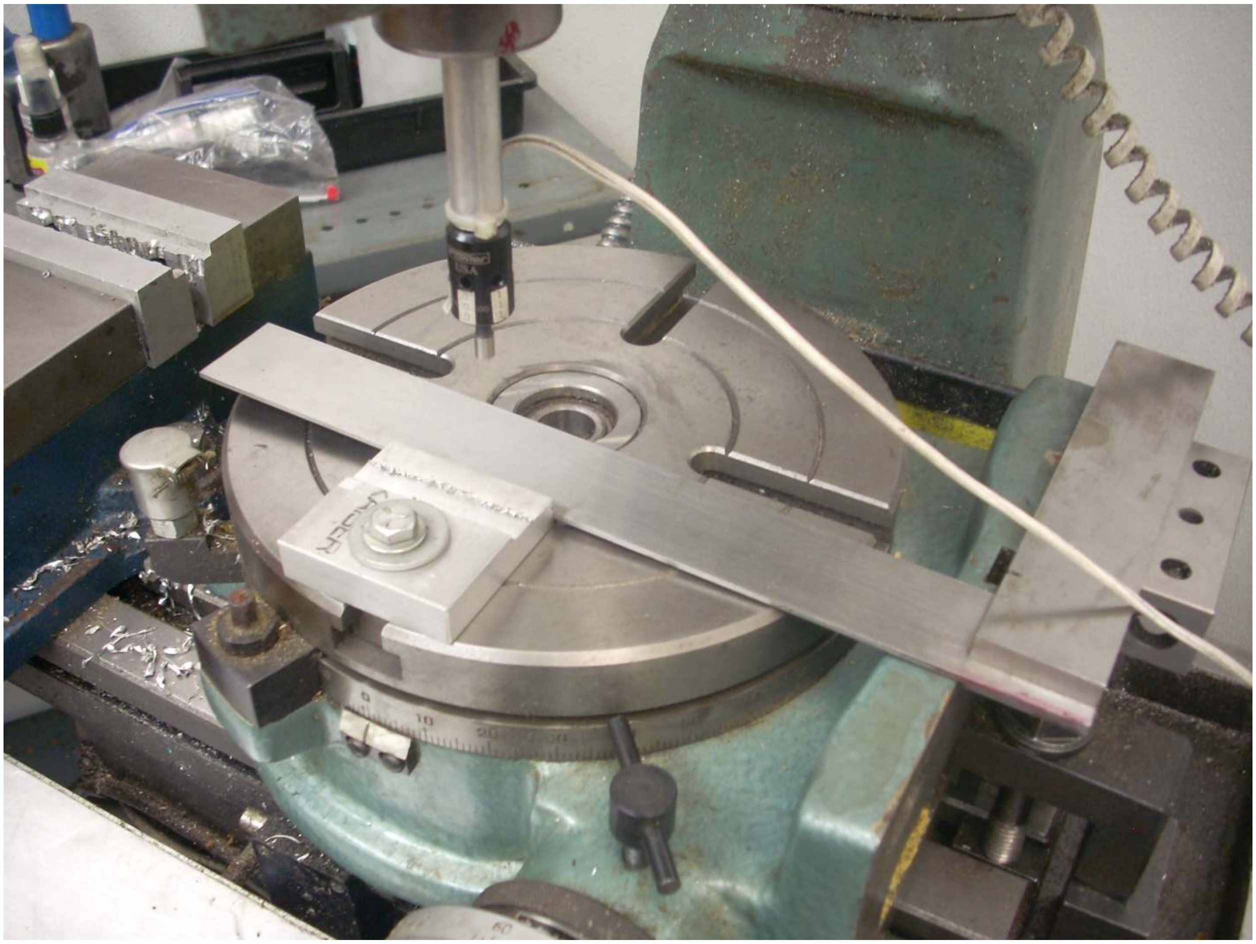
Here is my simple fence that clamps into a T-slot.



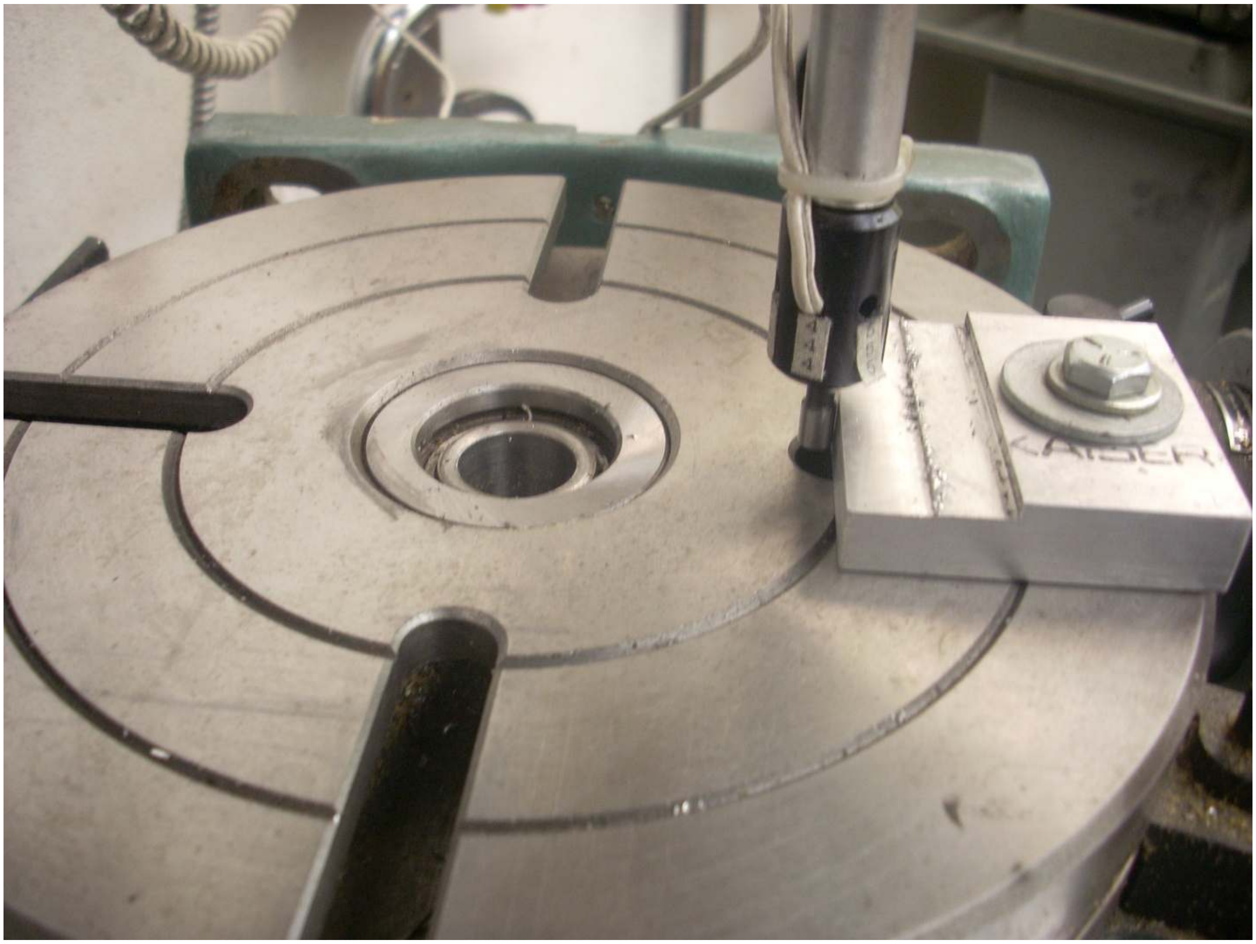
Not much to it. The rounded bar in the center gives a rough alignment of the fence to the T-slot but I still need to use my machinist square to get it right.

So much for my compound, it is time to try out the procedure and tools. The first step is to align the center of rotation of the RT with the center of rotation of the spindle and set it as (0,0).

Rotary Table Alignment



I will use an Electronic Edge Finder (EEF) and a block of metal clamped to the RT. The RT is set to 0º and the crank gear has been disengaged for now. I'm using my machinist square to get the block parallel to the X axis.



First I will align the center of rotation along the Y axis. I run the EEF, set with no tool offset, up to the block and set zero.

The RT is spun 180º. Then I move the Y axis until my EEF again contacts the block. Half the distance traveled is my Y = 0. The procedure is repeated for the X axis. I now have (0,0) set at the center of rotation of the RT. The crank drive is re-engaged.

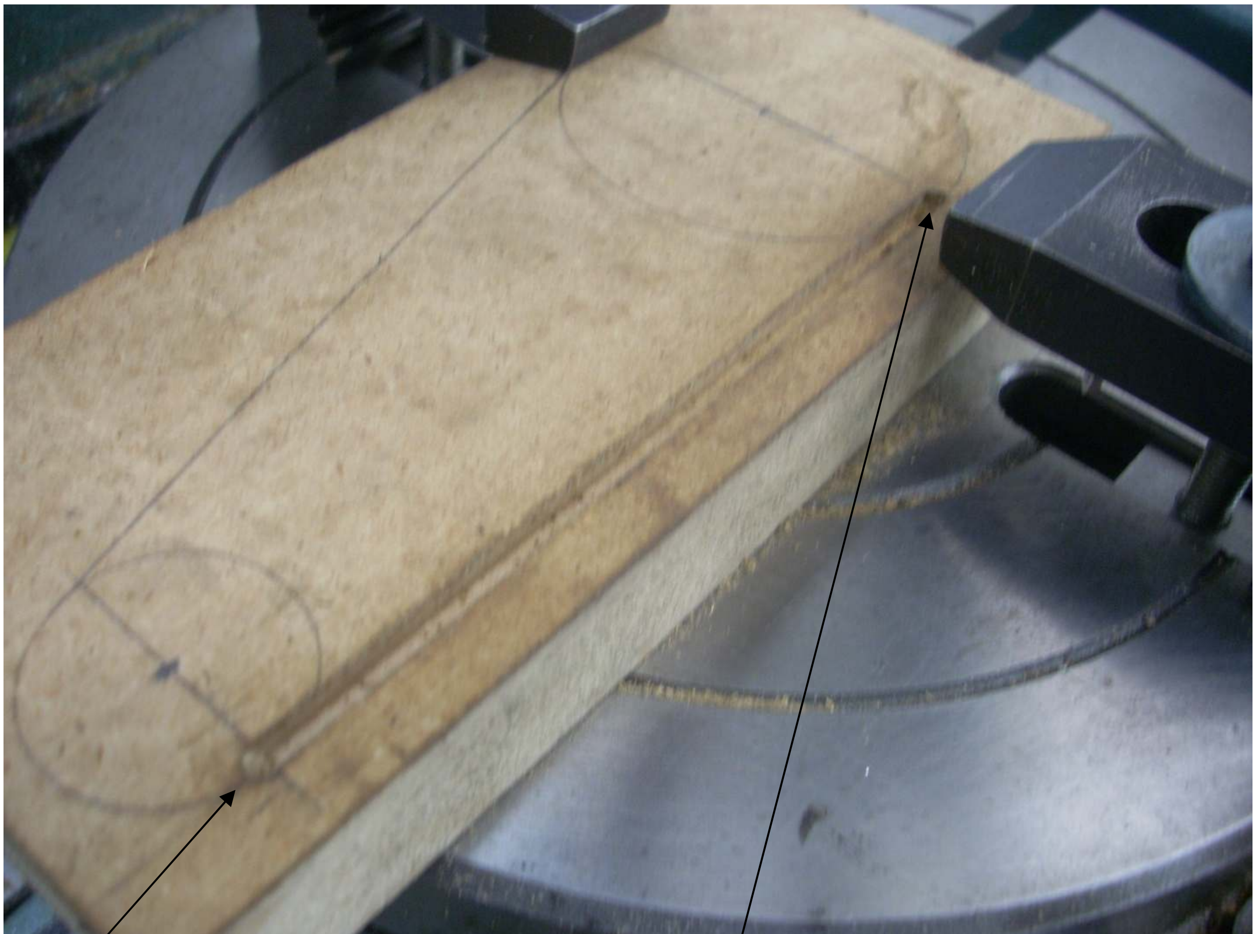
I like this procedure because it is a single pass process and is quick.

Machining

I will be machining MDF with an 1/8” end mill. This will prove in the ideas without a lot of wear on my machine.

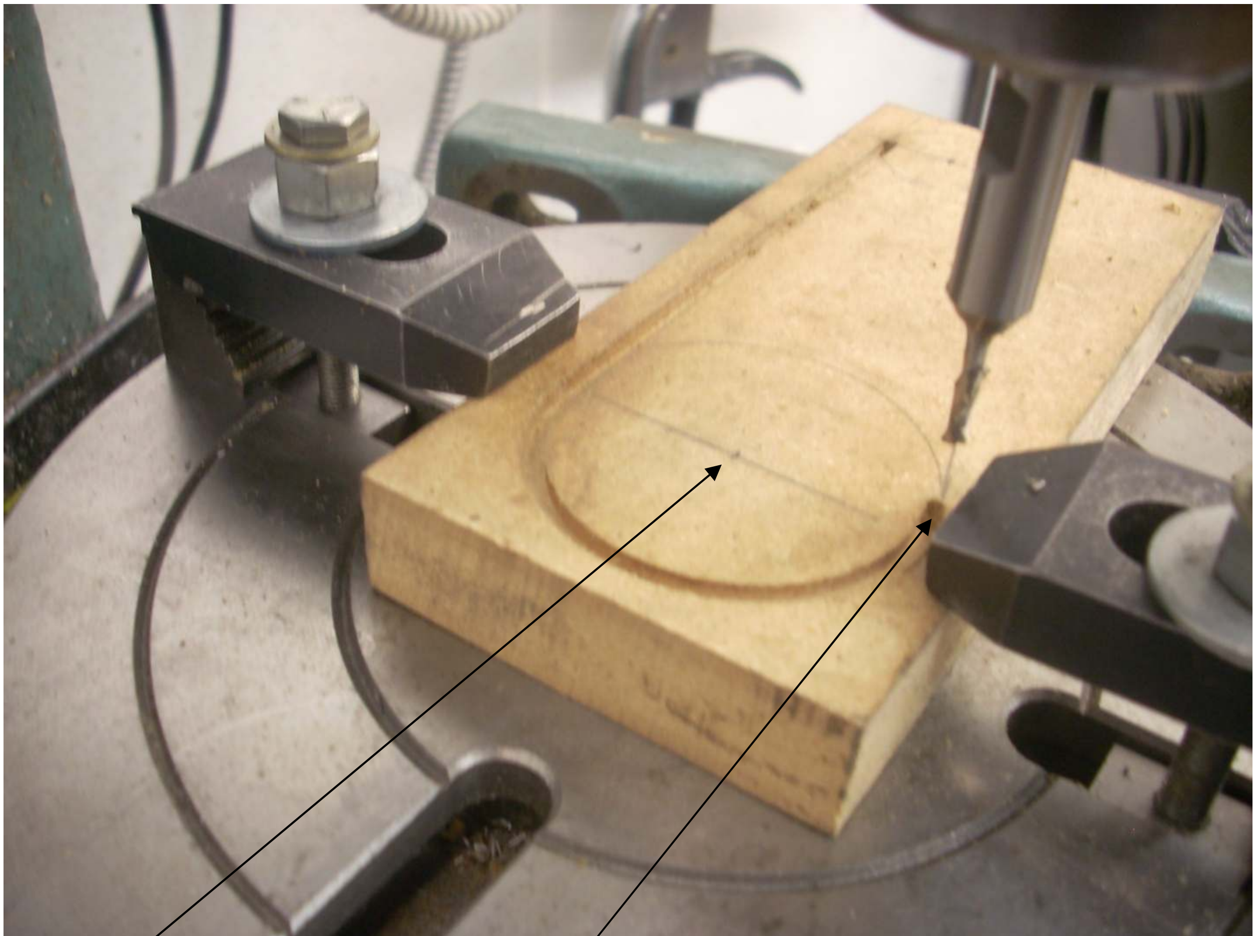
I’m using a spud mounted in a collet to hold the block of MDF while my machinist square aligns the edge. Recall that I want the center of the large arc to be aligned with my center of rotation. After clamping down the block, I mounted the end mill.

I then move my mill table so my cutter is at point “A”. The Y axis and RT are locked. With the mill running, I lowered the cutter down about 0.1”.



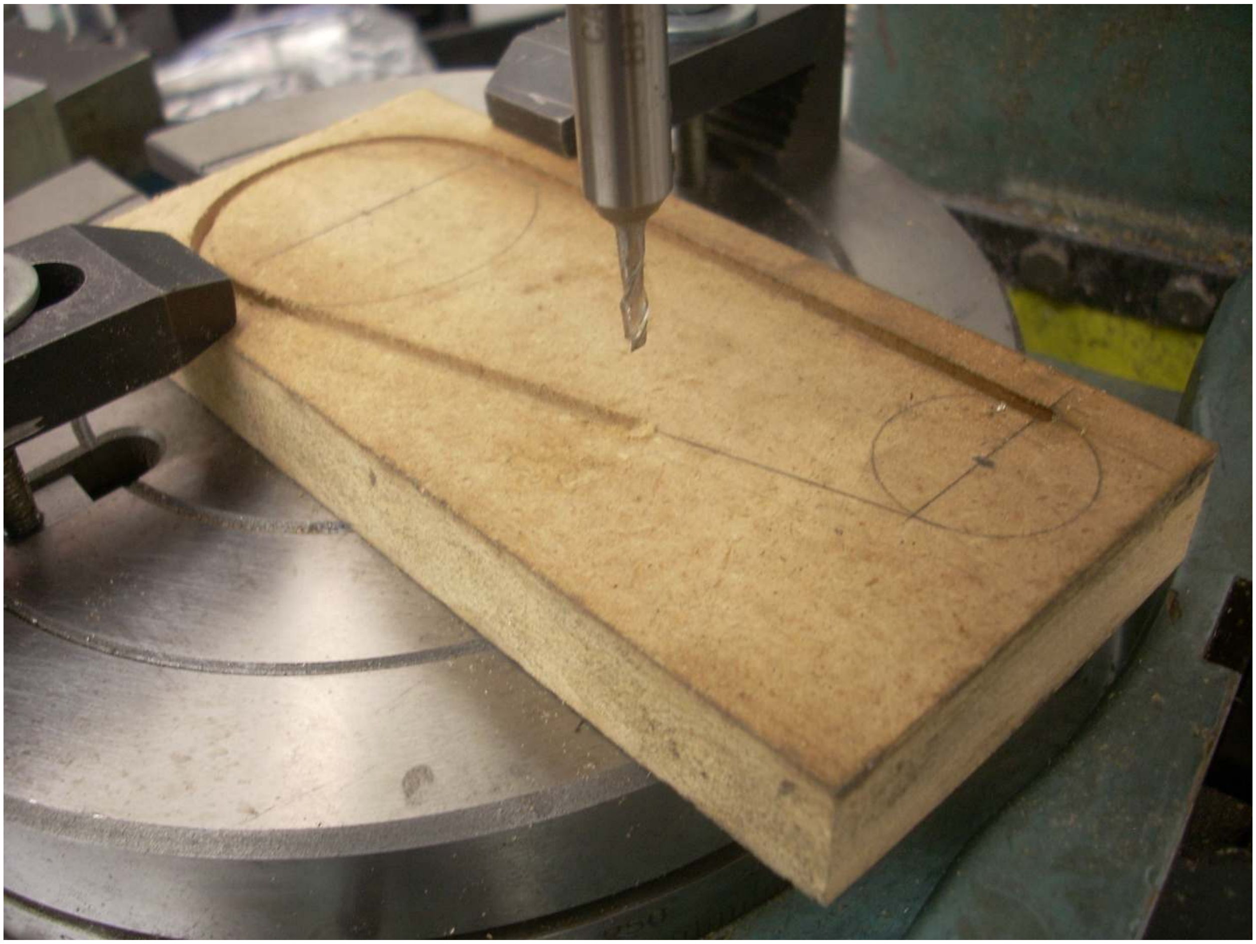
“A”

The X axis feed is driven until I get to point “B”.



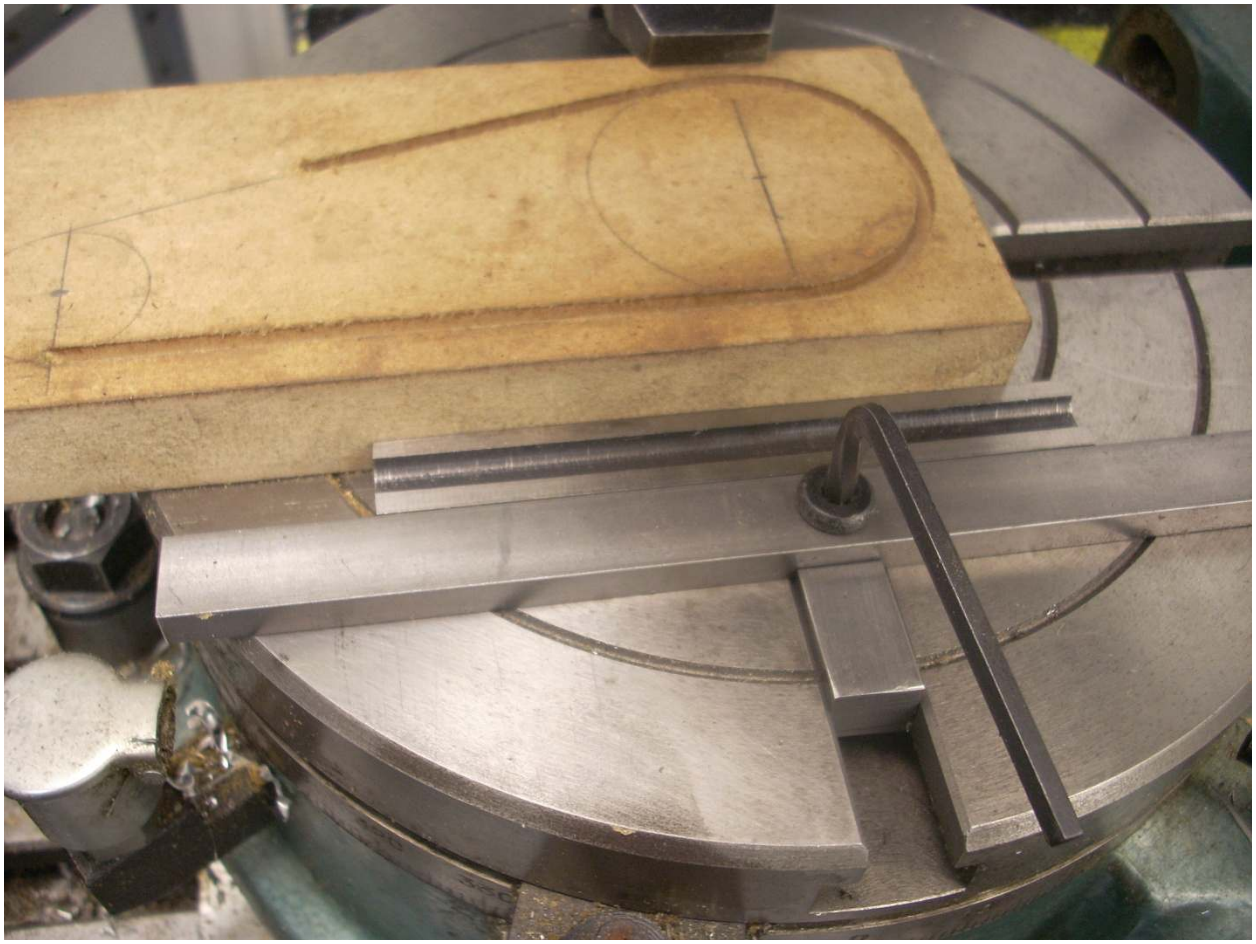
Point "C" Point "D"

The X axis is locked and the RT is unlocked. I then turn the table from 0º over to 194.2º or 194º 12'. I have lifted the cutter here in order to take the picture but I could have continued with my next cut without stopping. The X axis is unlocked and the RT is locked.

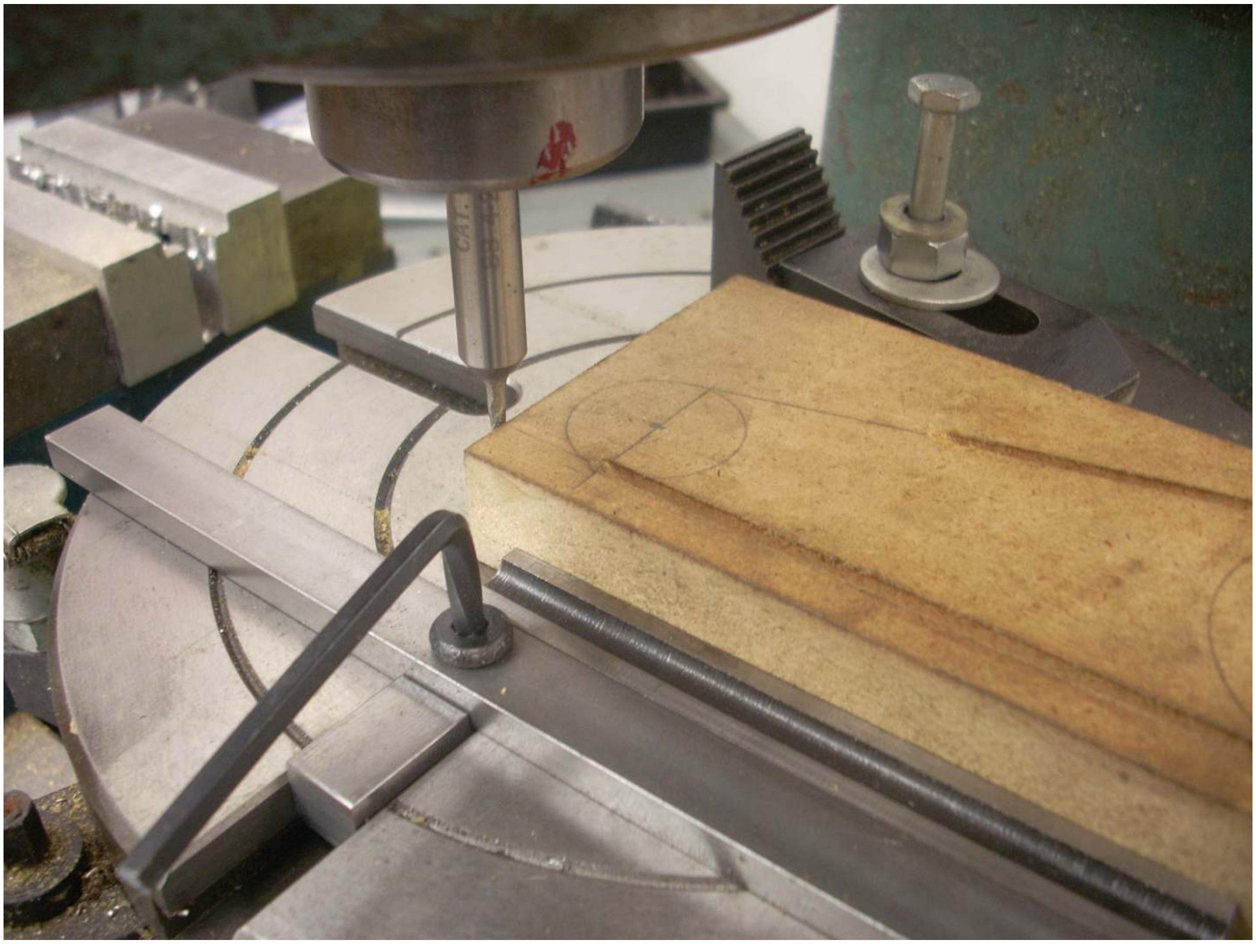


You may wonder why I stopped half way along the line. Well, I got caught in a lesson that keeps being repeated because I haven't learned it yet. I forgot to run the cutter over the full path before starting. My mill table is all the way to the left so the cut ends here. Time for plan "B".

I will go back to point "A" and cut the small radius. Then I can come at this unfinished line from the other end. I unlocked the RT, axis X, and axis Y. The RT is returned to 0º.

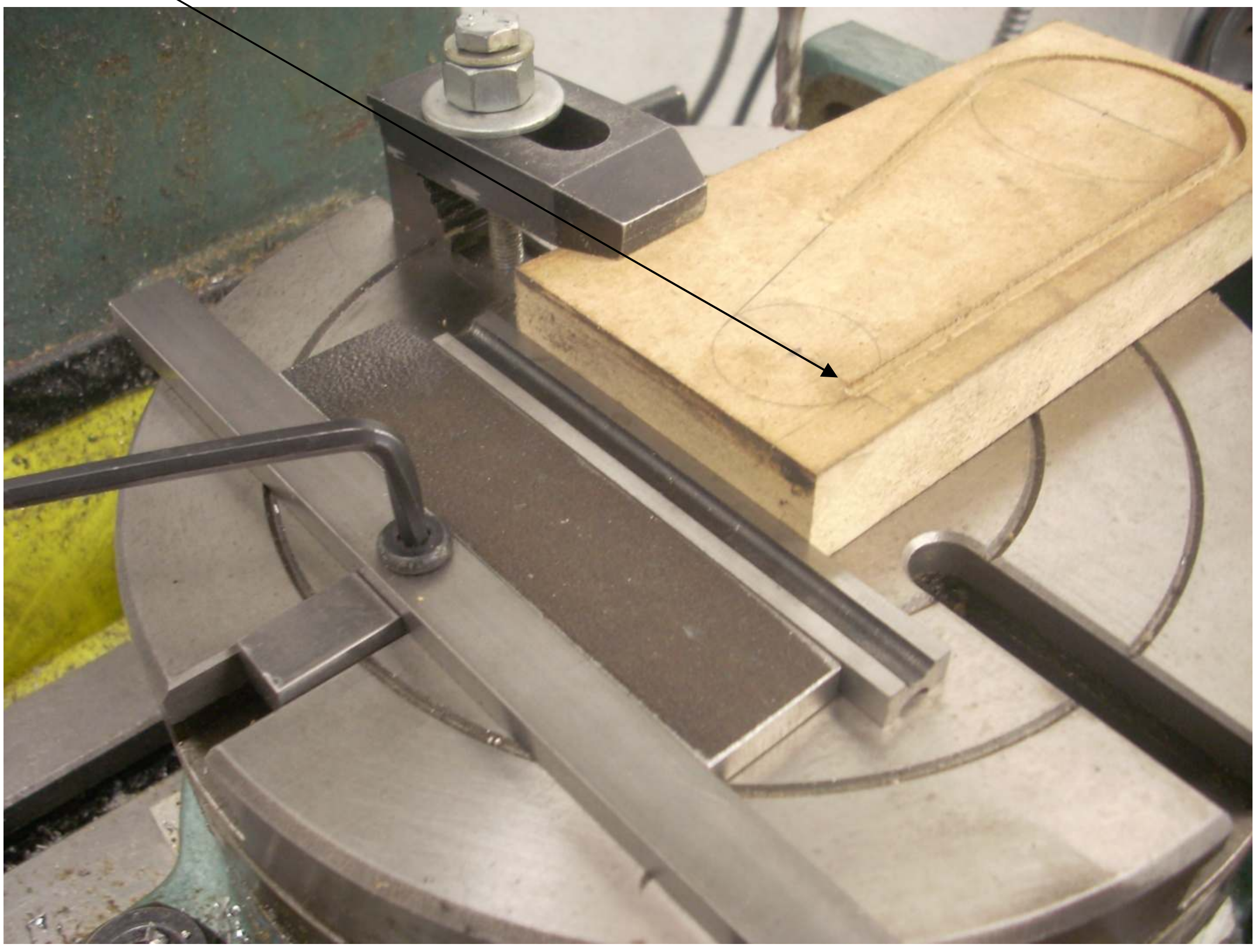


I have removed the front clamp in order to make room for my fence. I'm using a small parallel because the fence can't slide close enough to the MDF block. The block is used to align the fence before it is locked with the Allen wrench.

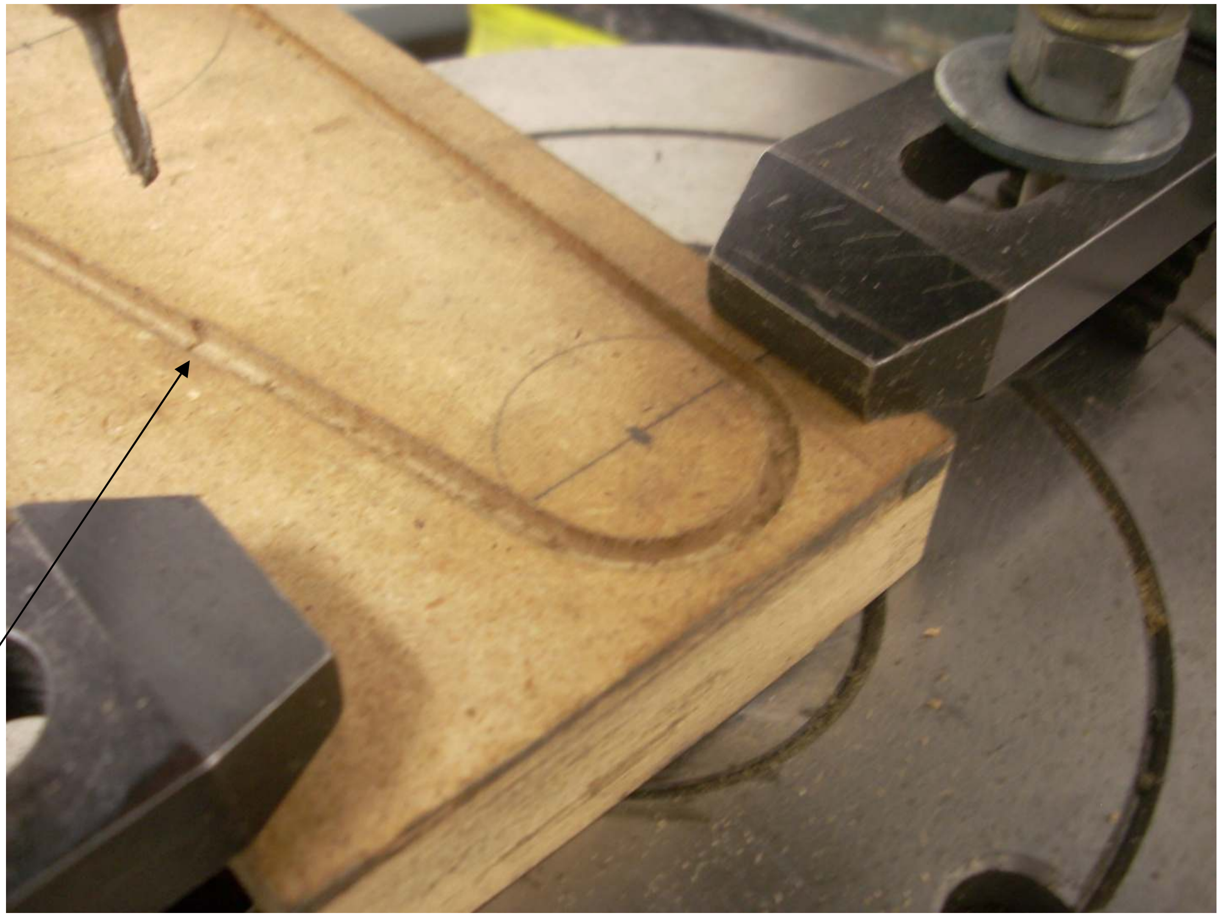


I need to move the block 4.000” along the X axis. Since I’m just trying to prove in the procedure, I have taken a short cut here that will later show to have hurt my accuracy. I am using the side of my cutter as a guide. It cut into the MDF slightly and caused error. It would have been far better to use a smooth rod. I am moving the block by hand out of the way of the cutter as I advance the X axis. When the mill table has moved 4.000”, I gently slid the MDF block until it contacted the end mill. The back clamp was then engaged.

Point “A”

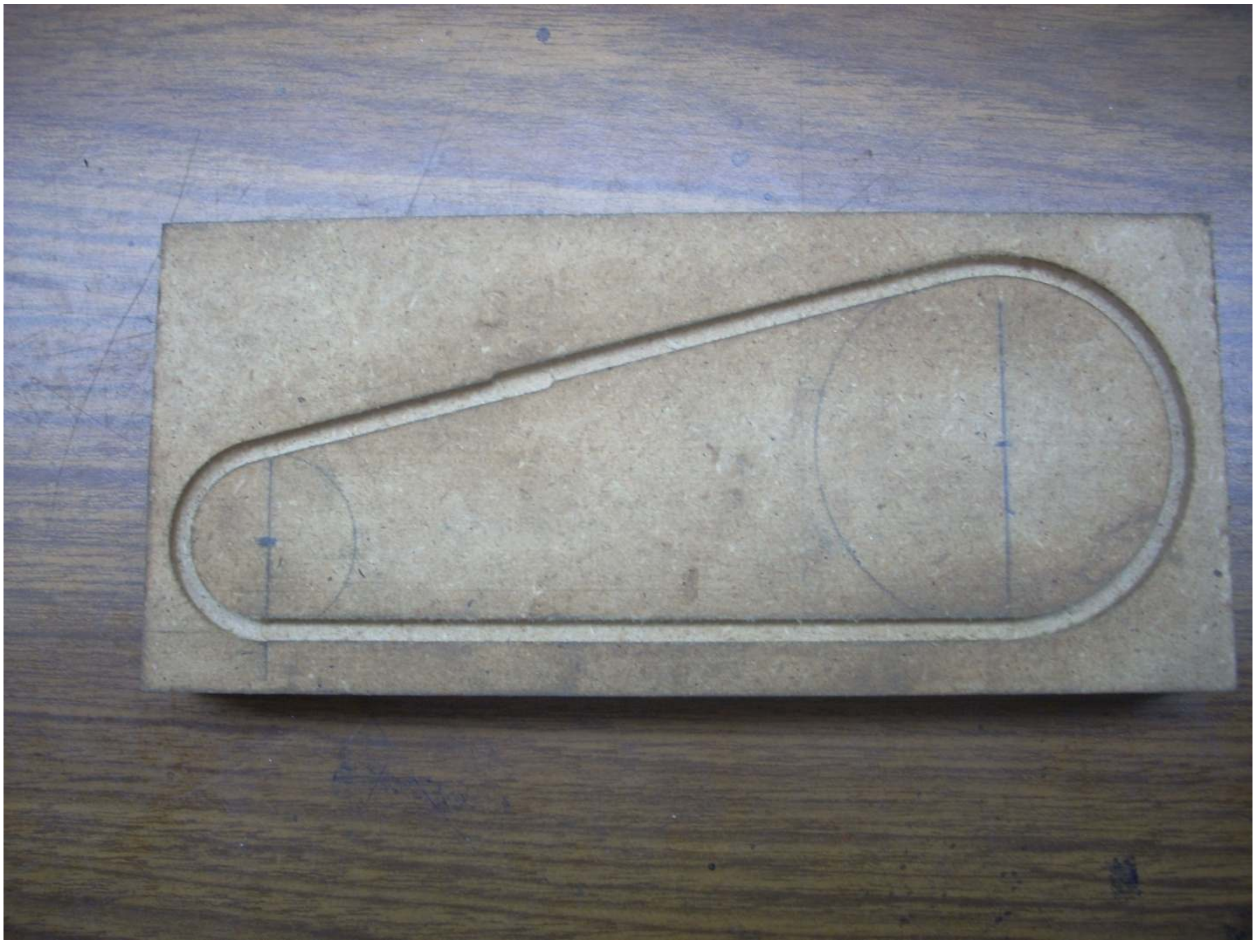


The process repeats for the Y axis. I had to use two parallels here. Not shown is the block being moved along the Y axis guided by the end mill.



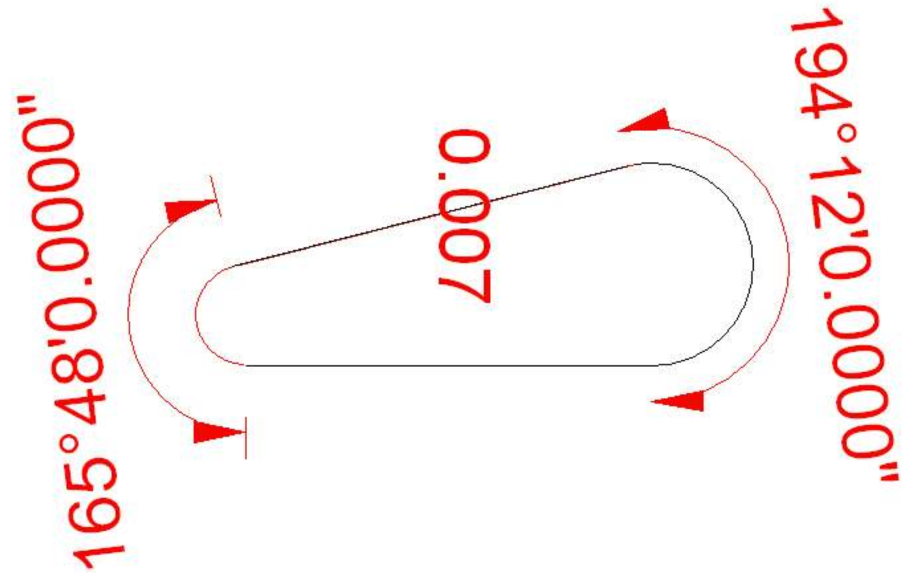
Here you see that I have made my turn on the RT and fed along the X axis to complete the top line cut. There was a small trap with the RT table here in that I had to turn the table counterclockwise 165.8º. This means that I must turn the crank until I reach 360º – 165.8º = 194.2º. If I had turned the RT until I read 165.8º, it would have been wrong. Do note that my large arc was 194.2º and since this is a closed figure being cut, the remaining arc must bring me a full 360º which it does. This makes a nice check of your math.

Note that the end of this cut does not perfectly line up with the end of the last cut. I am off maybe 0.01" along the Y axis. Maybe the MDF block was not snug against the fence or maybe the end mill cut into the block. Not sure, but I will try to be more careful next time.

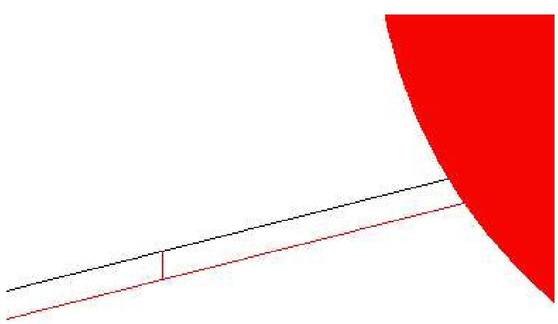


Sure looks like the math and procedure are valid.

A closer look by Dale King uncovered a subtle math error due to round off that caused the discontinuity in that top tangent line. I had the angle resolution set to 0.1º. This caused a 3’ error on both arcs which causes a 0.007” error at the midpoint of the top tangent.



The exact error value was found by increasing the CAD display resolution to the maximum, inputting arcs equal to the truncated values, and then drawing two 4" lines at an angle of 14.2º to match the arc's truncated values. One line is black and the other is red. The red line was attached to the end of the small arc. The black line was attached to the end of the large arc.



By zooming in on the top center of the figure, it was clear that the two lines are separated by 0.007" at their centers.

Lesson learned: be sure the resolution set in the CAD program is consistent with the ultimate use.

The General Case

I cannot predict what shape you may want to cut, but some general rules exist.

1. Accurately draw up the shape using CAD and dimension it to get your distances and angles. Be sure the resolution of your dimensioning tools is consistent with the resolution of your mill table and rotary table positioning indicators.
2. If you are going to cut the shape out of a rectangular block, be sure the block is machined square first as its edges are going to be your references. Otherwise, mount block on a square plate.
3. Transfer the design from CAD to the block with easy to see layout lines.
4. Trial mount your RT with the block on it to verify you can reach all parts of the block.
5. Write down the sequence you must follow to perform the cut. Keep in mind that you must be at 0º in order to use the fence to move your center of rotation around the RT.
6. Run through the procedure with the cutter above the block to insure there are no surprises.

Acknowledgements

I wish to thank my good friend Larry Gill for insuring the clarity of this article. Thanks to Jeff Anderson for finding my center to center error. Thanks to Bill Moll for explaining to me about the X axis and tangents to the arc. Thanks to Dale King for finding the round off error.

What Next?

My hope is that others will read this article and send me both questions and comments. This input will be used to improve the document so all can benefit. All of us are smarter than any one of us.

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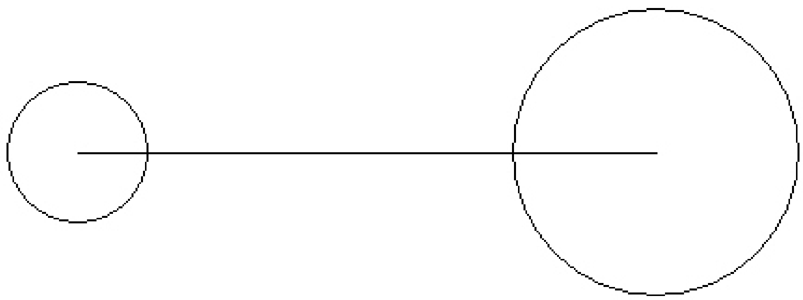
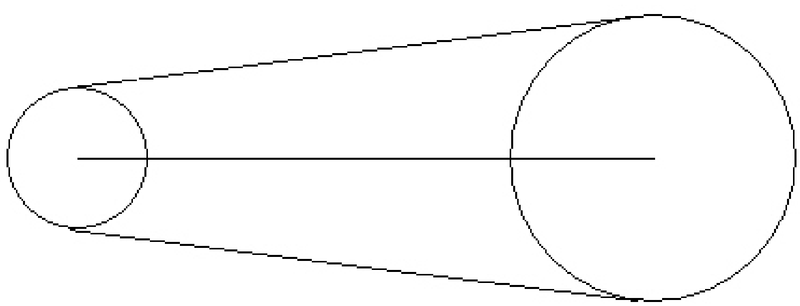
Appendix

The missing steps in drawing the figure have been added here rather than rework the body of the article. Jeff Anderson was very perceptive to see that I was not drawing the circles with a center to center distance of 4.000”. In fact, the distance was 4.031”.

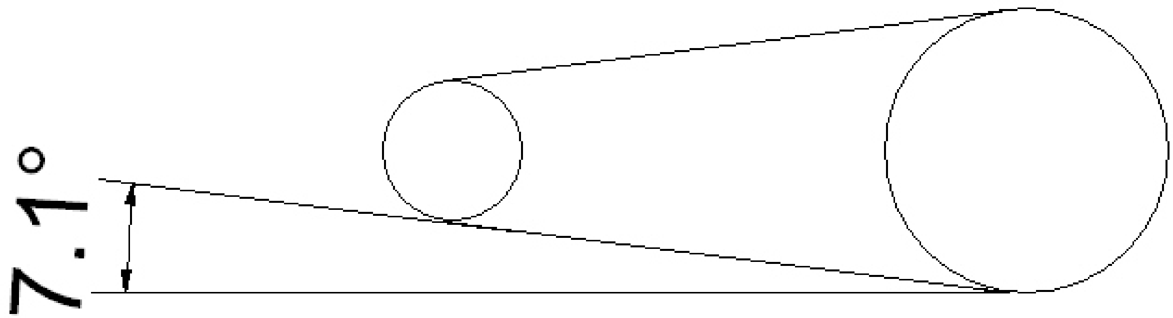
OK, Jeff, I’ll meet you half way. Say I really wanted a center to center distance of 4.031”.



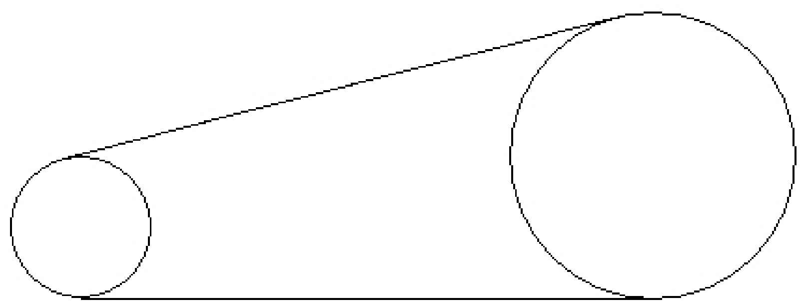
I have drawn a line 4.031” long. My 1” diameter circle is centered on the left end and my 2” diameter circle is centered on the right end.



I then used my tangent line tool and drew in the top and bottom lines. I now have the same figure as shown on page 4. One more step will make it more usable: rotate the figure so one of the tangent lines is parallel to the X axis.



Using my CAD's measurement capabilities, I can easily find how much to rotate the figure so the bottom tangent will be horizontal. I then use my rotate tool to turn it counterclockwise by 7.1º.



I now have each tangent 4.000" long and the center to center distance is 4.031". The lower tangent is parallel with the X axis.