Chapter 2

THE MINIMILL

With the concept of the Axtrusion complete, it was decided to showcase the Axtrusion with a small milling machine. The machine is called the Minimill

The basic functional requirements of the Minimill are:

- It should be a three (3) axis machine.
- It should have a minimum work volume of 300 mm x 300 mm x 300 mm (12 in x 12 in x 12 in).
- There should be additional clearance in the Z axis direction for tooling and fixturing.
- The machine should be able to cut parts to with an accuracy of at least 25.4 microns (0.001 in).

2.1 Some Competing Machines

After searching the web and reading trade publications it was concluded that small milling machines currently available can be divided in to two categories.

2.1.1 Small Hobbyist Machines

These machines range in price from about $500 to about $2000. They may or may not be computer controlled. Most of them are glorified drill presses with an XY stage. Few of these machines appear to be stiff enough to do precision work in materials other then wax.

2.1.2 Small CNC Machining Centers

These machines range in cost from about $20,000 to upwards of $50,000. These are small production machines typically used in prototyping and making injection molding dies. They have optional tool changers and a variety of size and speed spindles. All the vendors surveyed list their machines' accuracies in terms of the servo/controller accuracy. I.E. how accurately the machine can move the tool, but they do not give an estimate for how accurately the machine will cut the parts. Determining a machine's accuracy requires an knowledge of how the machine will deflect under the load of the cutting forces. None of the engineers spoken to at these companies knew how large those deflections might be.

Some Competing Machines

The Compact DMC™ (left), and the XV Tabletop™ (middle) Machining Centers by Defiance. The Benchman™ Series (right) by Light Machines.

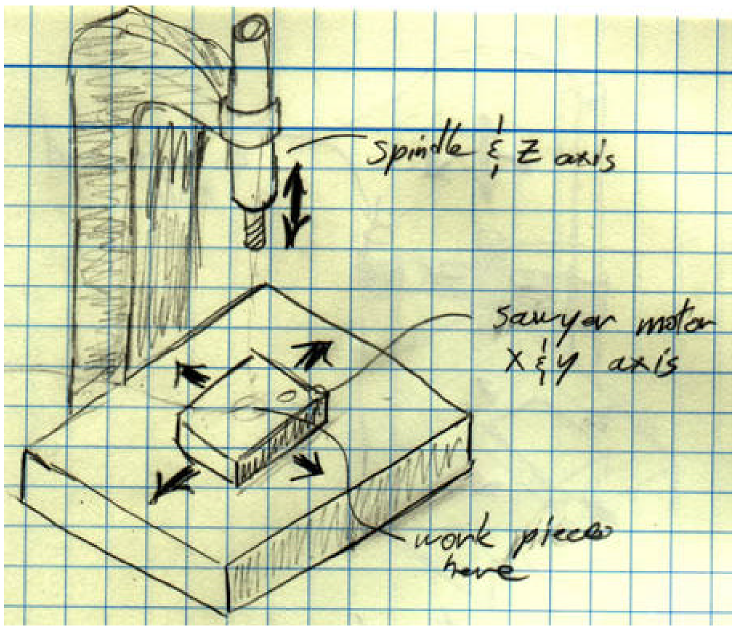
2.2 Some Initial Concepts

Some stick figure sketches were made for several machine concepts. The main criteria at this point for eliminating concepts are the distance between the tool tip and the linear motion points on the axis. Designs that have excessively long distances between the tool tip and motion points will be more susceptible to Abbe error. These designs are eliminated for this reason.

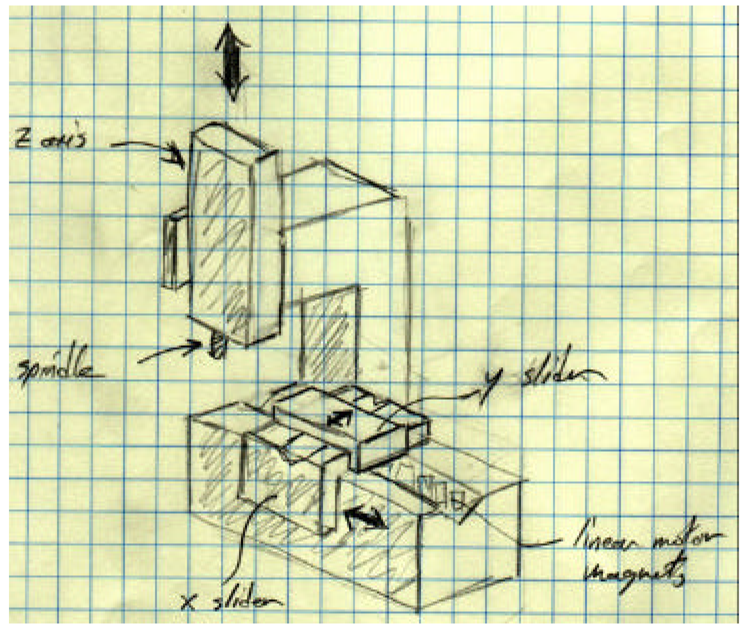
Some other considerations in the initial design of the machine was whether the tool should be vertical or horizonal. A vertically mounted tool requires less fixturing to hold the workpiece. A horizontally mounted tool is convenient for cutting chip removal (they can fall straight down). In a small machine, the spindle is likely to be one of the heavier components, so there is an advantage in mounting this lower down (as in a horizontally mounted spindle).

It is difficult to stack all three degrees of freedom on only the tool or the workpiece. The right-hand sketch bellow shows a concept where the tool moves in one degree of freedom (Z) and the workpiece moves in two (X and Y).

Some Initial Concepts



Sawyer Motor for the X & Y Directions. Traditional or Combined Unit for the Z axis and Spindle



Two Axtrusions on the base (X &Y) and an Axtrusion for the Z axis.

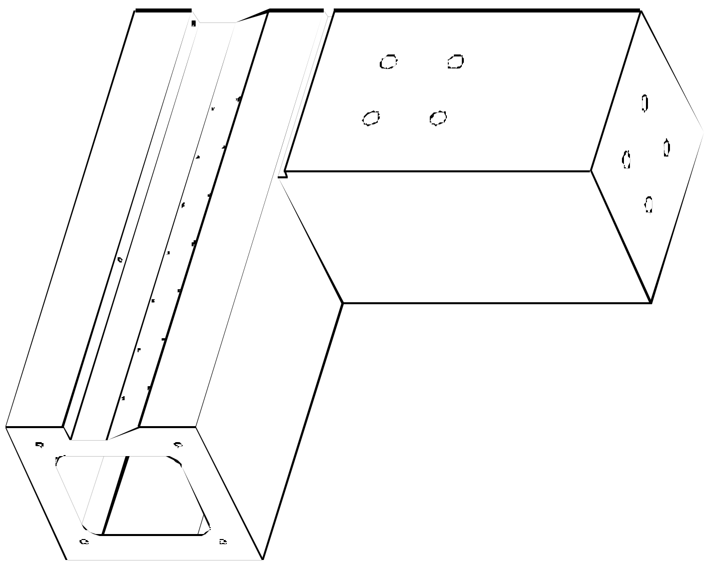
2.3 Two “L”s To Make a Machine

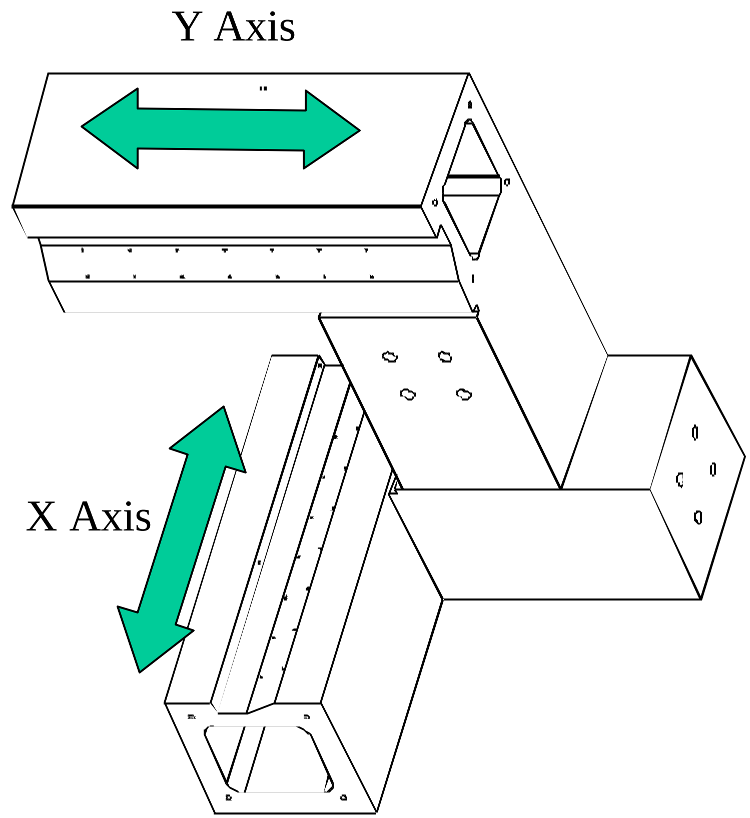
In the process of trying to decide whether the tool or the work piece should have two degrees of freedom, it was realized that two identical assemblies could be used to make a the X and Y axis of the machine.

This concept requires that two “L” shaped blocks be used for the base structure. By attaching these blocks, as shown below, workpiece on the base can move along the X axis and the tool can be moved on the Y axis above it.

Using identical assemblies in the construction of the two major axes of the machine allows for more efficient manufacturing. This is especially true if the major parts are cast in a process that easily produces in large quantities.

Two L’s Used to Make Machine





2.4 The Error Budget

The formulation of an error budget is an important step in ensuring that the machine will meet its accuracy goals. The types of errors were broken down into three main catagories. Each of these categories is initially allotted an equal share, 8.47 µm (0.0003 in), in the target accuracy of 25.4 µm (0.001 in).

2.4.1 Static Deflection Errors

These are the errors associated with compliance in the machine structure, bearings, spindle, and tools. It is important to keep in mind that the target accuracy only needs to be met on the finish pass of the cut, when the machine is not running at full power. Therefore the cutting forces will be much lower. The final cutting forces were assumed to be no greater then 30 N (6.7 lbs). The cutting tool was assumed to have a deflection of 3 microns. The compliance in the carriage bearings causes the carriage to rotate when a moment is applied. This carriage rotation will cause a displacement error at the tool tip. The maximum allowable magnitude of this displacement determines the maximum allowable carriage rotation. For the worst case error budget the carriage rotation was estimated for when the Z way was fully extended. When the Z way is completely extended the carriage rotation in the Y and Z carriages causes the greatest amount of error. In this state the error caused by the X carriage rotation is minimized because the tool tip is very close to the X carriage.

2.4.2 Thermal Expansion Errors

Heat generated by the machine components and changes in the ambient temperature will cause the machine to expand and contract. The errors associate with these changes should be no more than 8.47 microns (0.0003 inches). The parts of the machine most susceptible to thermal errors are the ways.

2.4.3 Control and Alignments Errors

This category includes all the errors caused by the pitch and yaw of the linear motion elements, the errors in the position encoders and controller, the misalignment of an axis, and any error motions in the X, Y, and Z carriages. The magnitude of these error motions were not known until the prototype Axtrusion was built.

The Error Budget

With an overall machine goal of 25.4 microns (0.001 inches) the allowable errors are split among three main errors sources.

Static Delfection Errors	[microns]
Tool Deflection	3.0
X Carriage Roll	0.5
Y Carriage Roll (@ full extension)	1.5
Z Carriage Roll (@ full extension)	1.5
X Way Deflection	0.0
Y Way Deflection	0.2
Z Way Deflection	1.6
Total Static Deflection	**8.3**

Maximum Carriage Roll	
Due to Delfection	**[arc sec]**
X	0.3
Y (@ full extension)	1.0
Z (@ full extension)	1.0

Thermal Expansion Errors

$\alpha_{al} := 6 \frac{\mu m}{m \cdot K}$ The coefficent of expansion of granite

$L := 600mm$ The maximum length of one of the ways

$\delta L := 8\mu m$ The maximum length a way may change

$\Delta T := \frac{\delta L}{\alpha_{al} \cdot L}$ $\Delta T = 2.2K$ The maximum temperature change that the machine can tolerate

Control and Alignment Errors

Maximum error motion in carriage roll, pitch, and yaw for each axis is 2 arc seconds

2.5 MiniMill Major Components

A convenient feature of the MiniMill is that there are only three major moving parts: the X carriage, the Y carriage, and the Z way.

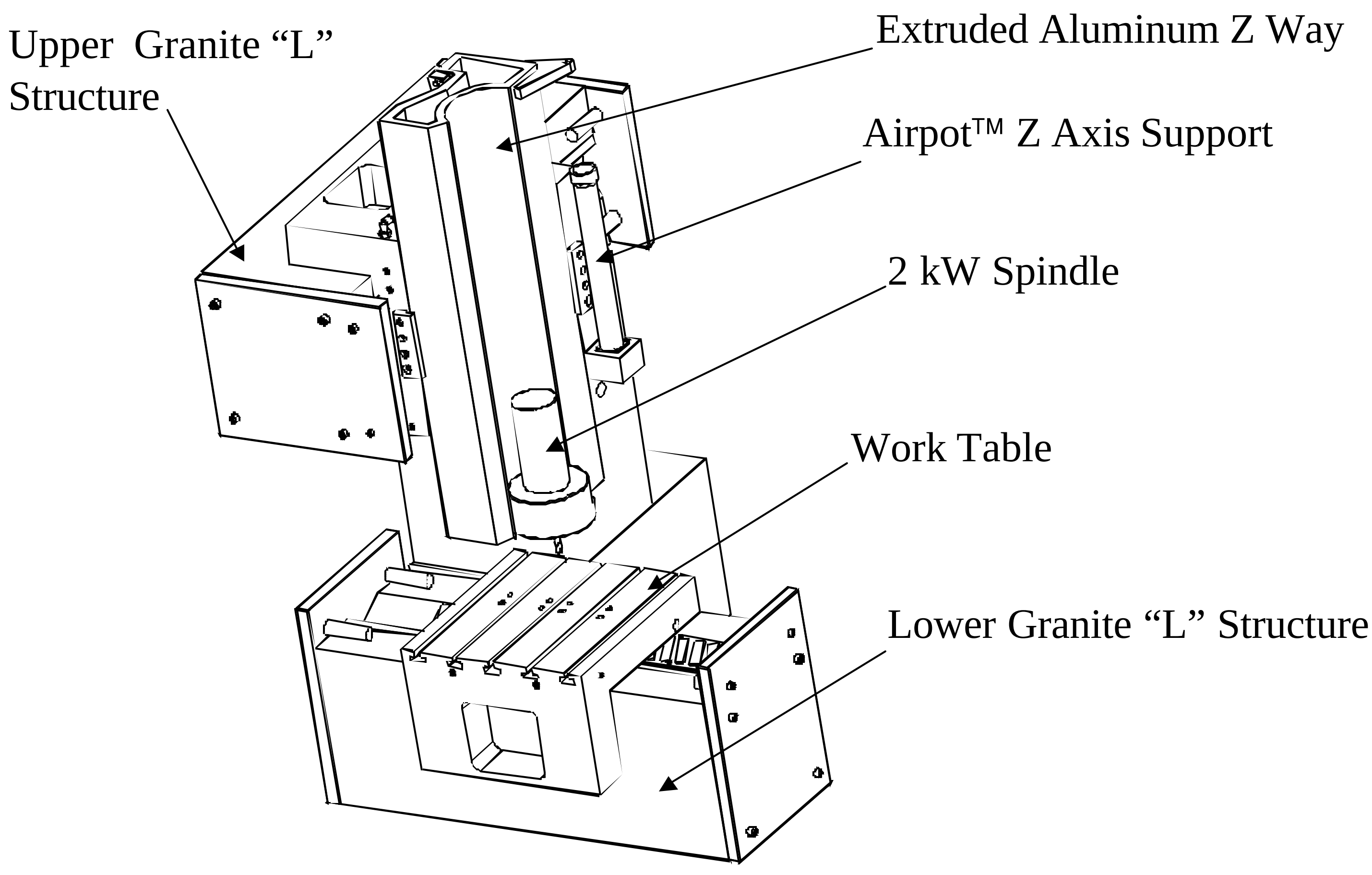
The Z way is an extruded piece of Aluminum. The two precision surfaces are ground and then the whole piece is hard anodized. The linear motor magnet track is attached to the Z axis and the motor coil and air bearings are attached to the Y carriage. The only wiring that has to move with the Z axis is the spindle wiring.

The Airpot™ piston is used to support the weight of the Z axis while it is floating.

The 2 kW (2.7 hp) spindle could be supplied by a company like Fisher Precision Spindle of Berlin CT, USA.

The work table is 300 mm (12 inches) square and the X and Y axis are configured to allow the tool to reach any point on the table.

MiniMill Major Components



2.6 Simple Stiffness Check

The largest sources of compliance in the Minimill are the air bearings. A quick check of the machine stiffness is performed early in the design process. This check only accounts for the tool tip error due to compliance in the air bearings. If the air bearings can meet the performance criterion specified in the error budget, this aspect of the design is likely to succeed. The displacement of the tool tip can be no more than 1.5 microns (0.000059 in) each for the Y and Z carriages.

When the Z axis is completely extended there will be a moment arm of about 500 mm (19.6 inches) on both the Z and Y carriages. With a maximum cutting force of 30 N this results in a torque on the Y and Z carriage of 15 Nm (11.3 ft.-lbs). Using the bearing stiffness measured on the prototype axtrusion of 100 N/micron (570,000 lbs/in), these parameters are entered into the basic stiffness model shown below. This model indicates that the tool displacement due to the rotation of each carriage at full Z extension under the 30 N load is about 1.4 microns. This is within the specifications of the error budget.

Axtrusion MiniMill™ Quick Check of Bearing Compliance

$L_b := 230mm$ Distance Between Bearing Centers

$L_t := 500mm$ Distance From Center of Stiffness to Tool Tip

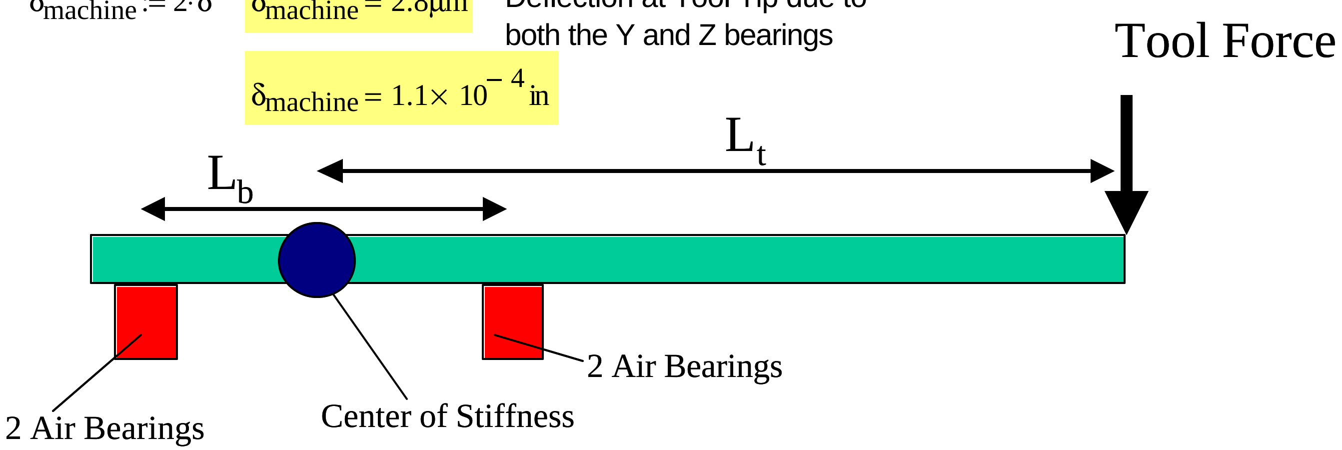
$K := 200 \frac{N}{\mu m}$ Stiffness of a Pair of Air Bearings

$F := 30N$ Force Applied at Tool Tip

$\delta := \frac{L_t^2 \cdot F}{0.5 \cdot K \cdot L_b^2}$ $\delta = 1.4\mu m$ Deflection at Tool Tip due to one set of bearings

$\delta_{machine} := 2 \cdot \delta$ $\delta_{machine} = 2.8\mu m$ Deflection at Tool Tip due to both the Y and Z bearings

$\delta_{machine} = 1.1 \times 10^{-4} in$



2.7 A Finite Element Check

The stiffness results were checked with a finite element analysis (FEA) of the machine. The displacement predicted by the FEA is within 1.2 microns of the simple stiffness check. The FEA results shown below use an estimated individual bearing stiffness of 40 N/µm (it agrees with the simple check when 40 N/µm is entered in the simple model).

One of the most critical parts of the FEA model is to correctly model the air bearings. The air bearings are modeled as blocks of equivalent stiffnesses. The size of the air gap in the actual machine is on the order of 10 to 20 microns. If the actual dimensions of the air pad model were used they would be 100 mm x 50 mm x 12 µm and 150 mm x 75 mm x 19 µm. The finite element size is approximately the air pad model's smallest dimension. If the actual dimensions were used the air pad models would have approximately 30 million elements each. The CAD software also has trouble creating features so thin compared too the rest of the machine. So for the FEA model the air gap was made 4 mm thick. This reduces the number of elements in each pad by 5 orders of magnitude, allowing the program to solve it.

The air is modeled as an solid with a Young's Modulus such that the air pad model will have the same stiffness as the actual air bearing. The equivalent modulus is calculated by

$$E_{equiv} = \frac{K \cdot t}{A}, \tag{2.1}$$

where K is the desired stiffness of the air pad model, t is the thickness of the model, and A is the area of the air pad.

TABLE 2.1 Equivalent Young's Modulus for Air Pad Models

Parameter	100 x 50 mm	150 x 75 mm
K [N/µm]	40	110
t [mm]	4	4
A [mm^2]	5000	11,250
E_{equiv} [MPa]	32	39

Air bearings modeled in this way provide stiffness in all directions. Actual air bearings only provide stiffness normal to the surface that they are running on.

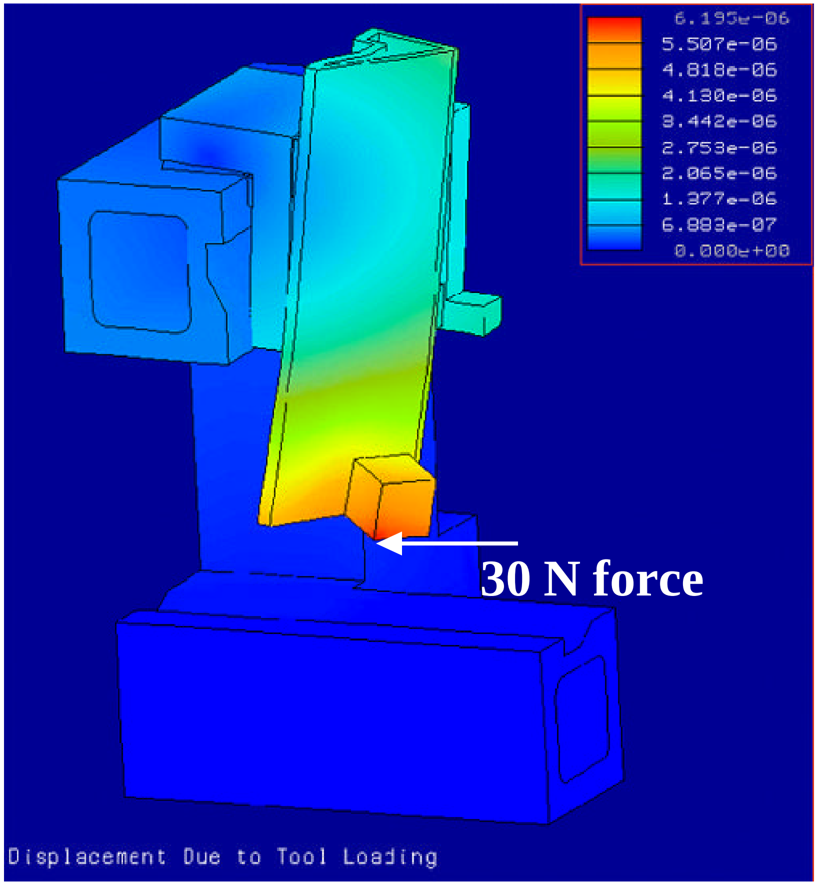
Axtrusion MiniMill™ Displacement Due to Tool Loading

A 30 Newton tool load was applied to the Z axis at full extension in the negative X direction.

The FEA estimated 6.2 microns of displacement with this load, when the bearing stiffness was estimated to be 40 N/micron.

This yields a machine stiffness of: 5 N/micron (27,000 lbf/in)

The quick stiffness check (previous slide) gives an estimate of 5 µm for deflection at the tool tip (w/ a bearing stiffness of 40 N/µm.) Did the extra 1.2 µm come from the deflection of the Z axis itself?



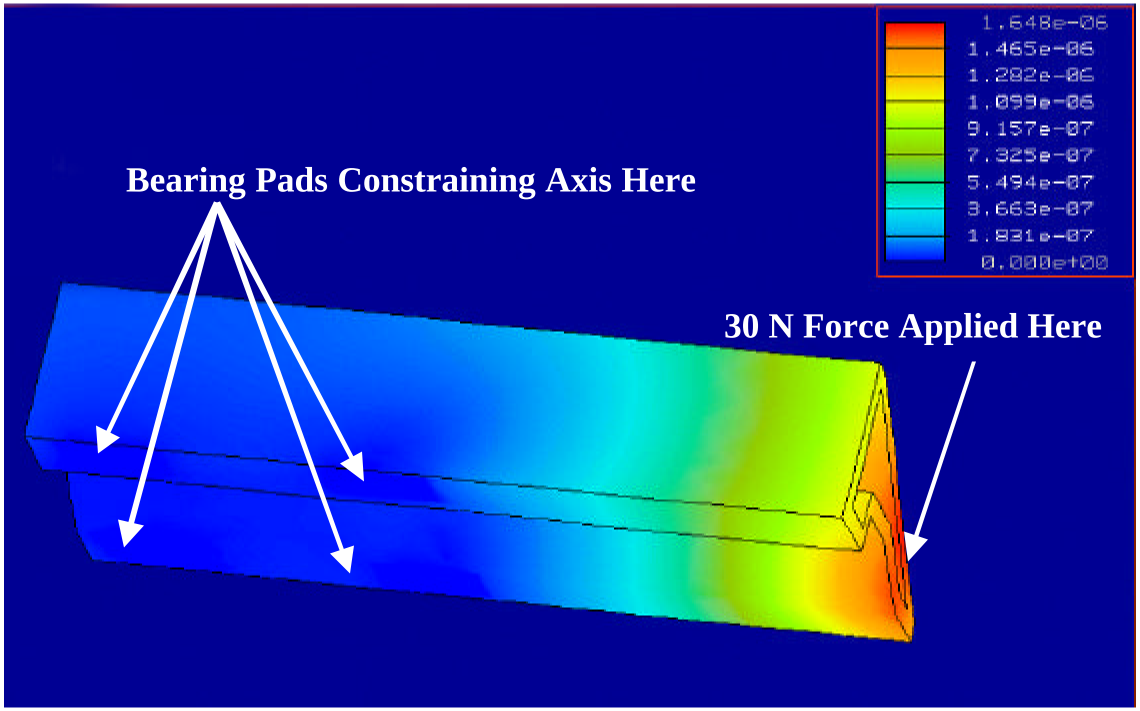
2.8 An FEA Check of the Z Axis

After the air bearings in the carriage the next most compliant component in the structural loop is the Z way. The Z way is an extruded aluminum piece.

It is hypothesized that the difference in displacement between the simple stiffness model and the FEA of the machine can be rectified by checking the displacement due to the deflection of the Z axis.

A Finite Element Analysis of the Z axis was run and confirmed the hypothesis.

Checking the Compliance of the Z Axis



Under a 30 N force at full extension the Z Axis deflects 1.6 microns.

This rectifies the difference between the simple stiffness calculation and the FEA of the whole machine.

2.9 Displacement Errors Due to Gravity

The Finite Element Analysis in Section2.7 only calculated the displacement due to a tool force. Gravity will also cause displacements in the machine. The FEA was rerun to estimate the magnitude of these displacements. The results of this second FEA run can be divided into two categories.

2.9.1 Error Inducing Displacements

As the Y carriage moves out the Y axis, its mass deflects the Y way further. When the Y carriage is at the extreme of its travel, the Y axis will droop about 20 microns (0.0008 in). This error in the vertical deflection can be eliminated by mapping it out and having the controller drive the Z axis way to compensate for it.

2.9.2 Non Error Inducing Displacement

The compliance of the Y and Z carriage bearings will cause the Y and Z carriages to rotate under the load induced by gravity. Because this rotation is constant for all Y and Z positions it does not contribute to the errors in the machine.

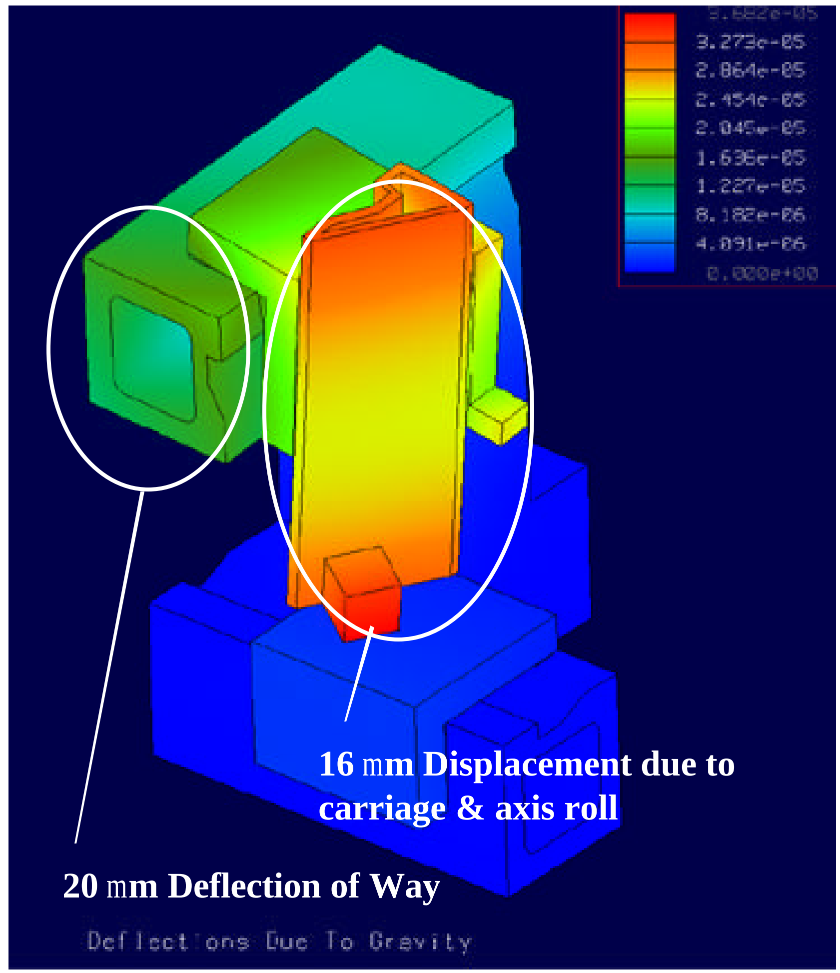
Axtrusion MiniMill™ Deflection Due to Gravity

There are two components:

- The deflection of the Y way
- The Roll of the YZ Carriage

The deflection of the Y way is proportional to the position of the YZ Carriage on the axis. When the YZ Carriage is at the end of the Y way there will be a deflection of about 20 microns for the polymer concrete version. Solutions are listed on the next slide.

The Roll of the YZ Carriage is independent of the either the YZ Carriage Position or the Z Axis position, So it should not effect the accuracy of the machine much.



2.10 Remaining Work on the Minimill

The Minimill design is not complete. However, it has been demonstrated that the Axtrusion linear motion element makes the design very simple. The work remaining to be done on the Minimill includes:

- Detail design of position encoder mounting hardware.
- Detail design of cable carrier mounting hardware.
- Detail design of the Z axis and spindle mount.
- Detail design of the bellows mounting hardware.