# A STUDY ON A NOVEL 5-AXIS MACHINE TOOL USING DIRECT DRIVE

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## INTRODUCTION

In an effort to improve the manufacturing productivity of precise and complex parts, manufacturers would like to use precision machine tools as high volume, versatile manufacturing tools. The productivity of precision machine tools can be improved by applying high speed machining methods to the classical orthogonal multi-axes machines. Machine versatility can be enhanced with a machine design that allows the cutting tool to approach the workpiece from many angles, quickly and precisely. In this design versatility is achieved by using a novel method to rotate and position the spindle as much as 90 degrees from the horizontal through the use of linear motors and electro-pneumatic clamping. Thus creating a machine tool that approaches the rigidity of the classic machine tool structure with some of the versatility found in parallel kinematic machine tools.

## BACKGROUND

The two most common methods used for powering movement in machine tools are the ball screw and linear motor drives. Ball screw drives are less expensive and can provide accelerations as high as 1 g. But they also can introduce errors from gear wear and backlash and have low natural frequencies, which make them less suitable for precision high speed machining. Linear motors can provide high accelerations, high thrust forces and are very stiff dynamically. Therefore they may be more suitable for precise high speed machining [1]. However they are more expensive, generate more heat and can produce high attractive forces between the moving and stationary sides of the motor.

The two most common structural designs discussed in the literature are the classic orthogonal multi-axis machine and the hexapod parallel kinematic design [2,3,4]. The classic multi-axis machine is more rigid statically, dynamically and thermally. However the less rigid, less thermally stable hexapod design has the advantage that it can provide more machining flexibility through its ability to provide a larger variety of paths that the cutting tool can approach the work piece [3,4]. The classic machine tool design in its 5-axis form can provide a wider variety of cutting tool paths. But may not be able to provide these paths in a manor suitable for high-speed precision machining due to the error and relatively slow movement of conventional drive systems. Therefore the idea of this design is to create a machine that combines the rigidity of the classic machine tool with some of the flexibility of hexapod and use a linear motor drive system to provide the acceleration and accuracy needed for high speed precision machining.

## DESIGN APPROACH

A digital design approach was used for the design and analysis of this device. This entailed creating virtual prototypes of components and assemblies using

IDEAS CAD software. This distributed model of the device was used for static and modal analysis using the finite element method. Large motion analysis of the device was done by creating a lumped model using ADAMS software. Lumped masses where used to represent the major components and stiffness matrices were used to represent the compliance of the rail carriages. ADAMS was also used to model the performance of the pneumatic ballast actuators of the system using an analytical model of the actuators inserted into ADAMS. For all of the analyses done, a performance criteria was used to judge the virtual performance of the component or assembly. Thereby testing aspects of the design without creating a physical prototype.

## CONCEPTUAL DESIGN

A conceptual design of the device is shown below with a 500 by 500mm square work piece that shows the working range of the device. In Figure 1 the spindle is in its full vertical position for machining on the top surface. Figure 2 shows the lower horizontal position. By supporting the work piece with a 2-axis table, which can rotate about its vertical axis, the device has the ability to machine on the top horizontal surface of the work piece and the 4 vertical surfaces. Thus achieving 5-face machining.

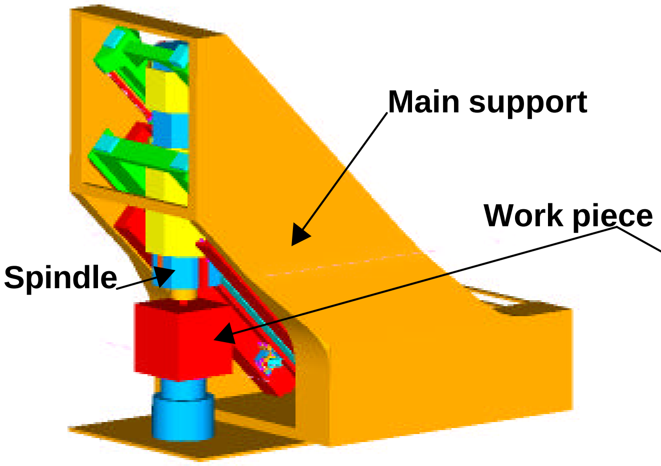

**Figure 1: Machining on top surface**

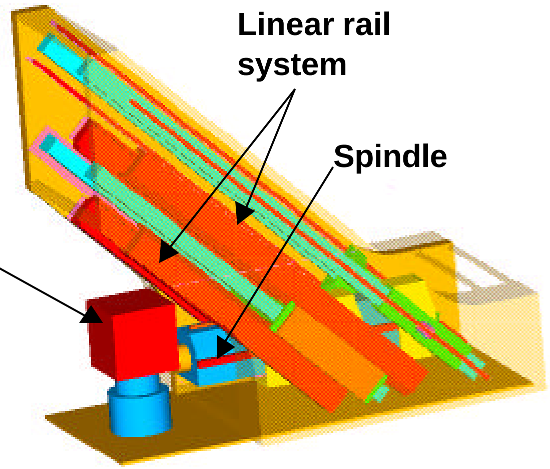

**Figure 2: Lower horizontal position**

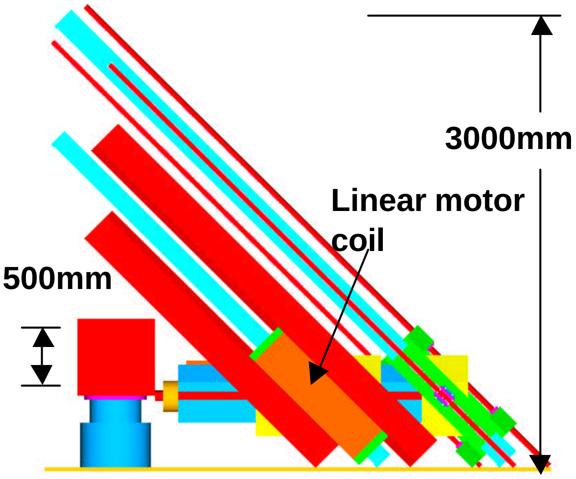

**Figure 3: Lower horizontal position**

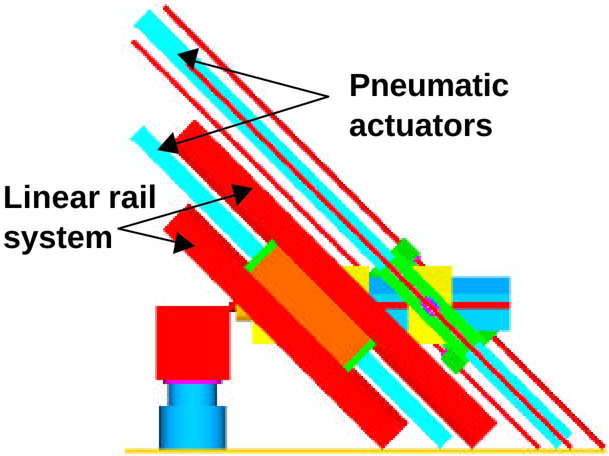

**Figure 4: Upper horizontal position**

Figure 2 also shows the main support of the device as partially translucent to show the placement of the linear guide rails. Figure 3 and 4 show the device without its main support. It shows the guide rails, pneumatic actuators and the linear motors. Figure 5 and 6 below show the device in intermediate positions at 45 degrees and 90 degrees respectively.

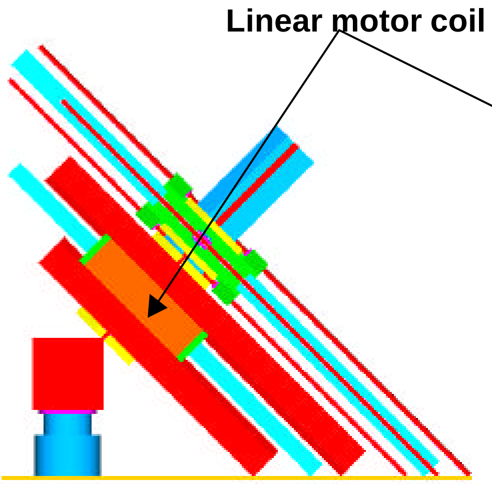

Figure 5: 45 degree position

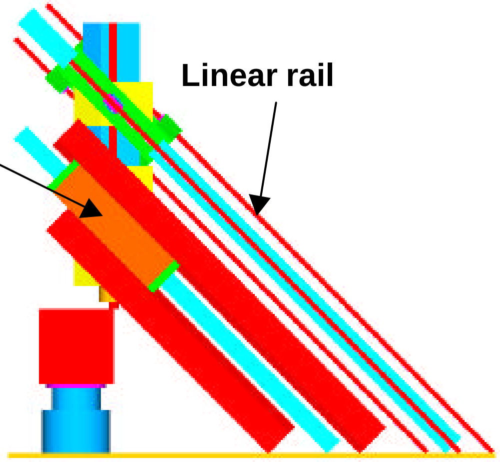

Figure 6: 90 degree position

Figure 7 shows the major components of the device: the spindle, the spindle supports, the frames and the linear motor coils. The frames support the motors and the pneumatic actuators and moves along the linear guide ways. The attached spindle supports, hold the spindle and can rotate up to 90 degrees while moving vertically. In addition, the spindle slides on rails in the spindle supports. Thus 3 axes of independent motion are possible. When combined with a 2-axis table, a 5-axis machine is created.

## OPERATION OF THE DEVICE

The operation of the device is as follows:

1. The spindle can move towards or from the work piece under the power of a GE Fanuc 3000B linear motor located under the spindle (not shown).
2. Vertical movement occurs through the combined thrust from the pneumatic actuators and linear motors that move the frames and spindle assemblies along the linear guide rails. The pneumatic actuators act as a ballast, offsetting the weight of the spindle and its assemblies against gravity. Thus allowing the linear motors to only work against the inertia of the assembly. There are three linear motors that provide vertical thrust. Two GE Fanuc 15000C linear motors in the front, on either side of the spindle and one 15000C linear motor in the rear along the side of the spindle.
3. Rotation of the spindle is caused by differential thrust from the front and rear linear motors and can be done while the spindle is being extended or withdrawn. Thus allowing for 2-axis motion of the spindle.

Rotation of spindle support is possible due to a 3 degree of freedom joint (3 DOFJ) as shown in Figure 8. This device allows for linear movement along 2 axis and rotation about another. This joint connects the spindle supports with the linear rail systems (not shown together). For precise single axis machining, the Zimmer electro-pneumatic clamps on the 3 DOFJ are activated, locking all movement except for the spindle on its linear rails. Thus allowing the spindle to move toward or from the work piece.

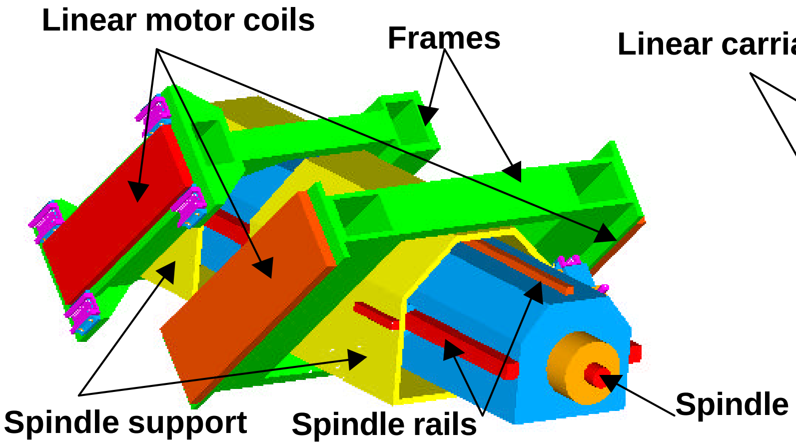

**Figure 7: Main components**

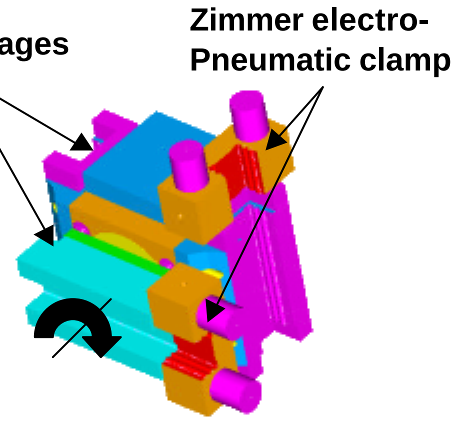

**Figure 8: 3 Degree of freedom joint**

## SIMULATED PERFORMANCE

Using the simulation approach previously discussed, a static, modal and large motion analysis of this device was performed. The static deflections of the spindle where shown to be less than 10 microns due to cutting loads and gravity. A motion analysis using 2-axis movement, to trace a 100mm circle showed deviations less than 5 microns at tracing velocities up to 167mm/sec. Positioning performance of the spindle, under power form the pneumatic actuators and linear motors, showed a maximum acceleration of 1.5 g's. These performance results were deemed acceptable.

## CONCLUSION

This design has been successfully simulated as a digitally engineered prototype. This work will be expanded to include an error budget analysis, which will be used to evaluate the ability to manufacture the device and the expected accuracy. This analysis will incorporate the static, dynamic, kinematic and thermal errors of device as derived from simulation work.

## REFERENCES

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