Design and Control Aspects of a new Meso-Milling CNC Machine

by

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Department of Mechanical and Industrial Engineering
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Abstract

Mechanical design concepts are presented for a new desktop meso-milling CNC machine. Concept selection criteria are discussed which highlight some of the challenges in mechanical configuration design, instrumentation and control. In conjunction, the conversion of an existing production 3-axis desktop milling machine into a meso-milling CNC machine is detailed. The retrofit process, which features electrical as well as mechanical design, control and instrumentation setup, helps to identify the design problems which must be solved, when creating a new desktop meso-milling machine tool which offers improved resolution, accuracy and repeatability while facilitating manufacturing flexibility.

Acknowledgments

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Chapter 1

12. Conceptualizing and Development of a Meso-Milling Machine Configuration

12.1 Introduction

12.1.1 Evaluation of the Meso Milling Equipment Market.

The term meso-milling is commonly used to define the milling of parts and part features which range in the size of 25 microns to a few millimeters. The technology required to produce parts at this scale does not differ significantly from the machines which are dedicated to producing macro-scaled parts, ie parts manufactured at a physical scale which is common across all industries. Consequently, there are currently many commercially available milling machines which are marketed for use in meso-milling and even micro-milling, which use conventional milling technology.

Currently the focus of much research into meso and micro milling has been the development of miniature tools and toolholders which are needed in order to remove material at an increment and resolution which is necessitated by the scale of the meso/micro parts and their features. Current feedstage actuation, spindle technology, sensor technology and control technology is judged adequate for producing commercial parts today. However, unlike the machining at the macro-scale, where the process is highly automated through standardized CNC methods, at the meso-scale, much emphasis is placed on the skill level of the machinist. The production of meso-scaled parts harkens back to a day where milling operations were the domain of highly skilled machinists and were manually intensive, generating much waste. These operations were not efficiently optimized for cycle time and were non-standardized in terms of operation times. Currently commercial meso milling machining operations require many hours of operator training and experience in order to efficiently produce parts and in order to grasp how minute errors stack-up and how the precision of the milling machine is affected by the choice of milling parameters including runout, feedrate and spindle speed.

This current state of manufacturing highlights the need for highly automated, flexible manufacturing centers which have been optimized for the production of meso-scaled machined parts. The key element in this new approach would be the research and development of machine flexibility and reconfigurability in order that the previously mentioned milling parameters can be optimized for a given object function. This object function may be cycle time, part accuracy or surface finish etc.

Currently the meso milling equipment market is very competitive with many large to small scale machinery manufacturers offering similar features at a similar price point. Please refer to Appendix A in order to view a cross-section of milling machines in this market, at various price points. As the table demonstrates, at the same price point, feed-stage actuation technology, spindle technology and sensor technology is very similar. Moreover, the machine metrics which are commonly advertized, feed stage resolution, repeatability and accuracy as well as spindle runout are very similar at each respective price point. Thus the question arises: How do the small, medium and large scale manufactures differentiate themselves to their prospective clients?

The manufacturers compete in many ways: The large, well-established manufacturers have focused on using advanced technologies in order to provide high-end, high precision machines. They have thus differentiated themselves by providing highly specialized machines. Given their presence in many OEM markets, they can afford this specialization in the meso and micro milling markets. Witness Fanuc's Robonano use of air bearings and linear motors on the feedstages, and the resulting 0.1 micron accuracy, and 1 nanometer resolution. These machines were intended for use primarily in the high precision optics and diffraction industries. These are substantial machines which are also intended for customers with a high manufacturing volume.

The medium sized competitors offer slightly lower accuracy, resolution and repeatability, yet provide a range of machines, features and accessories which are designed to satisfy customers' present and future needs. For example, they may offer a lower priced horizontal 3-axis machine, as well as a medium priced vertical machine which has the ability to add a modular 4th and 5th stages, and they may offer a wide range of accessories including modular fixturing, and quality inspection systems. The strategy adopted is thus the enroll customers and maintain these customers by satisfying their growing need for new equipment as their business grows.

The small-sized manufactures have focused on providing small desktop machines at the lowest price points. As would be expected they offer the lowest resolution, repeatability and accuracy. Yet the footprint of their machines is typically the smallest, and they offer their customers, typically small machining centers, equipment which is both affordable to purchase and requires little overhead to operate.

These three different market strategies are reflected in the choice of controllers used in the OEM CNC machines. The large manufacturers, such as Fanuc, source controllers made in another division of their company. These controllers are commonly closed architectures which do not permit much flexibility in modifying their computer code. This non-flexible approach is in keeping with the highly specialized nature of their machines.

The medium sized as well as the small-sized manufacturers typically source controllers made by third party vendors. Thus several OEM milling machine suppliers may source controllers made from the same manufacturer. The controllers used here tend to be open architecture controllers which offer the ability for the OEM to customize the controller design, as well as the design of the Human Machine Interface. A good example of a third party vendor which supplies this ability is Delta Tau. This company's controllers are currently sources by such OEM's as Microlution as well as many of the smaller sized milling machine builders in the meso-milling industry.

Open architecture controllers are thus favored whenever an OEM machine builder, or an end-user wants to customize their machines. Open architecture probably leads to much more innovative equipment, since an OEM machine builder must now differentiate himself through his use and application of this open architecture. The experimentation, development, and implementation of new controller algorithms and strategies are not only enabled by open architecture controllers, but is also stimulated through the very presence of these third party vendors of CNC controllers.

12.1.2 The Need for Developing a new Meso Milling Machine.

The above section has described how meso-milling is a machining application which requires highly skilled machinists, and is also an application where machining operations are still non-standardized.

Conversely, most medium and small OEM builders offer similar (ie. standardized) meso-milling machine hardware at similar respective price points. Yet at the same time, these same builders are being forced to innovate because of their use of common open architecture controllers.

These open architecture controllers enable customization and hence provide a method for the OEM to differentiation their machines from their competitors, through their choice of controller algorithms and Human Machine Interface design.

The apparent conflict between non-standardized, specialized machining operations and standardized, non-specialized machine hardware is thus currently being resolved through the design and implementation of ever more elaborate controller designs in order to reduce contour error and improve part accuracy. Yet the basic machine configuration of a meso-scale milling machine is unchanged from that of their macro-scale counterparts.

The above state of technology suggests that there is room in this market for a new machine which takes advantage of these new powerful, flexible open architecture CNC controllers and combines them with reconfigurable machine architecture. The resulting machine flexibility could thus be used to mathematically optimize any object function including machine cycle time, part accuracy, machine tool stiffness, and waste material among others.

This new machine would thus provide a rigorous mathematical way of optimizing the machining operation, and would thus be less reliant on the skills of a machinist specialized in meso and micro milling.

This new machine should also be small in size to accommodate the burgeoning small milling machining enterprises, and because the machine will be reconfigurable it will offer a larger range of use and thus will also potentially appeal to more medium-sized milling machining centers.

12.1.3 Product Part Specification

Meso milling is used to produce parts in many industries. Ranked from highest to lowest in demand for meso milling parts, these industries are the IT peripheral fabrication industry, the biomedical, the automotive, the household and the telecommunications industries[1]. In each of these industries, the discipline which is experiencing the most growth in recent years is the development and production of mechanical parts, followed, at approximately the same level of demand, by the development and production of optical components. Both of these product types can be characterized by their common use of 3-D sculpted surfaces.

Some common characteristics for 3-D sculpted meso parts include:

1. The use of materials, such as tool steel and optical glass which can have a hardness up to (HRc 50-56)
2. Part dimensions which can range in size from 0.5-5mm.
3. Feature dimensions which can be as small as 0.1 mm

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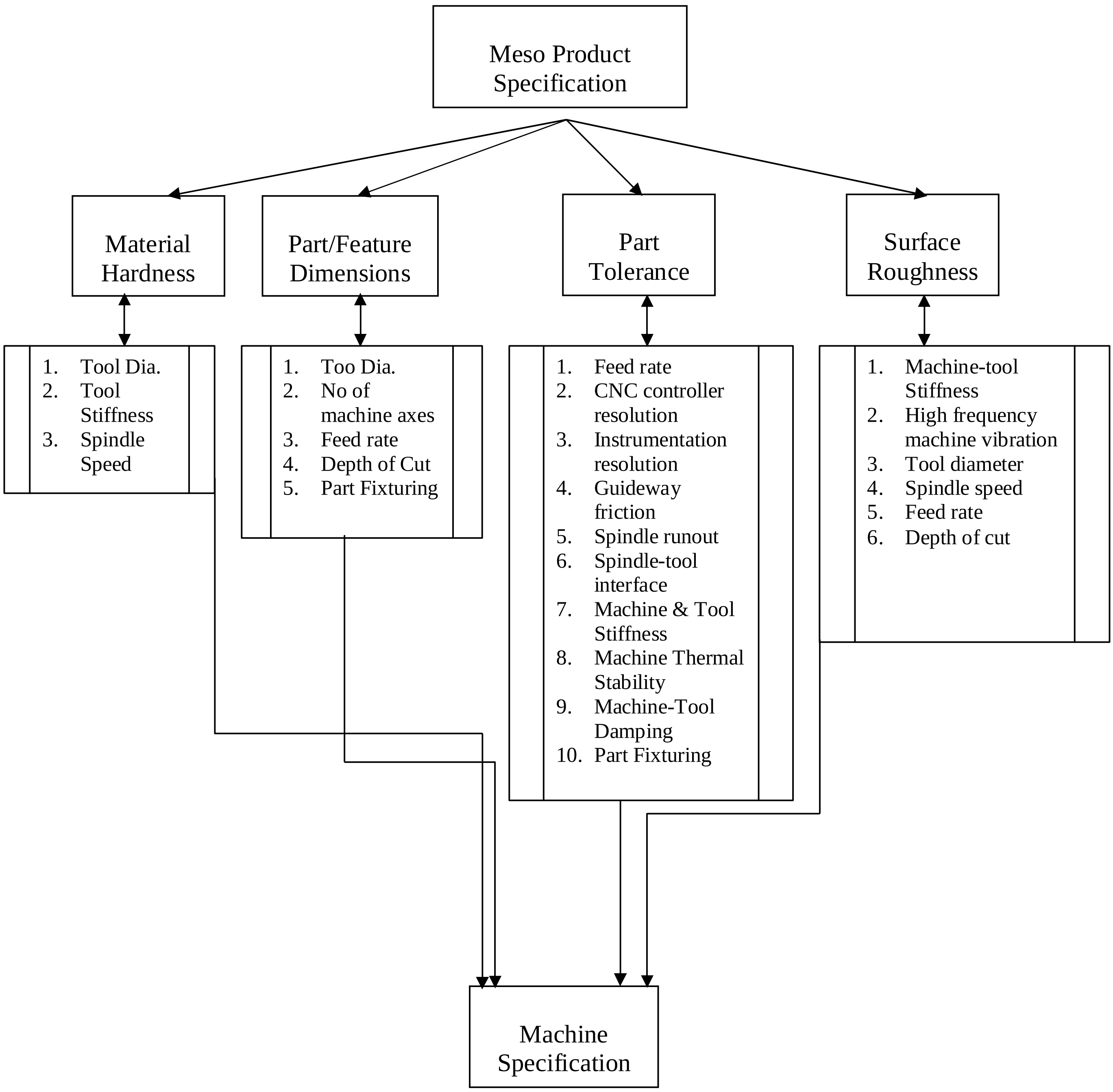
[1] Luo,X., Cheng, C., Webb, D., Wardle, F., Design of ultraprecision machine tools with applicatios to manufacture of miniature and micro components. Journal of Materials Processing Technology. Vol.167(2005). P.522.

4. Parts which have a dimensional tolerance of ±10 µm

5. Parts which have a surface roughness equal to R_a=0.2µm

Each of these key part specifications has a direct implication for the specification of the meso milling machine parameters. The chart below establishes the link between these key part specifications and the determination of machine specifications.

As the chart shows, producing parts in the dimensions specified will require very small cutters which will in turn demand very high spindle speeds in order to achieve the necessary surface cutting speed. Moreover, because of their scale, meso milling parts will require a very high part accuracy or small tolerance. As the chart shows, a whole series of machine parameters must be carefully chosen in order to ensure a part tolerance in the range of ±10 µm. These parameters are thus key considerations in the design of a new meso-milling machine. In order to achieve these goals, an advanced desktop meso milling machine would have to offer improved accuracy, resolution, repeatability and stiffness by optimizing the design of each of these key machine components listed below.


Meso Product Specification
Material Hardness
Part/Feature Dimensions
Part Tolerance
Surface Roughness
1. Tool Dia.
2. Tool Stiffness
3. Spindle Speed
1. Too Dia.
2. No of machine axes
3. Feed rate
4. Depth of Cut
5. Part Fixturing
1. Feed rate
2. CNC controller resolution
3. Instrumentation resolution
4. Guideway friction
5. Spindle runout
6. Spindle-tool interface
7. Machine & Tool Stiffness
8. Machine Thermal Stability
9. Machine-Tool Damping
10. Part Fixturing
1. Machine-tool Stiffness
2. High frequency machine vibration
3. Tool diameter
4. Spindle speed
5. Feed rate
6. Depth of cut
Machine Specification

12.2 Machine Design Objective:

The design objectives for this research initiative is to concept and develop a desktop meso-milling machine which offers improved accuracy, resolution and stiffness while efficiently using space and while providing manufacturing flexibility in order to optimally mill parts in the range of 500 microns to 5 mm.

12.2.1 Targeted Machine Design Specifications:

If the product part tolerance is in the range of ±10μm, then the milling machine should have a targeted overall accuracy of 1μm, or one order of magnitude less than the part tolerance. The overall machine accuracy of 1 μm has to be decomposed into tool (and spindle) runout as well as feed stage accuracy. The feed stage error and tool runout are additive. Therefore both need to be minimized through the selection of hardware and controller. However due to the small size of cutters used in meso-milling, and by implication, due to their lack of stiffness, there is inherently more potential to minimize the positioning accuracy than there is to minimize tool runout and deflection. Currently a positioning feed stage accuracy of less than 0.1 μm is targeted .as a goal. This level of positional accuracy is in line with the most advanced technology used on current commercial CNC meso-milling machines, as indicated in Appendix A Commercial CNC Machine Specifications.

Meso-milling machine tools can have a diameter as small as 0.1 micron, and in order to achieve a satisfactory tool life, tool runout on commercial machines is typically limited to 1µm[2]. This amount of runout can currently be achieved by using aerostatic or hydrostatic bearings on the spindle and a specialized HSK tool-spindle interface in order to increase tool center accuracy. An HSK interface design features a set of grippers internal to the spindle which centers the tool, and which uses centrifugal forces to cause the internal grippers to expand thereby firmly holding the tool in place. This type of design also avoids problems endemic to taper interfaces, whereby, due to increased operating temperature, the taper expands and the tool is driven further into the workspace, and the depth-of-cut accuracy deteriorates.

Since the proposed overall machine accuracy is 1µm, steps must be taken to lower tool runout to levels which are below what is common in industry: since we have targeted a feed stage position accuracy of 0.1 µm, tool runout should be less than 0.9µm.

Typical surface cutting speeds which are anticipated for use with this machine are approximately 16.5 m/min. This surface cutting speed is common for most carbon and alloy steels, and it correlates to a spindle speed of 50,000 rpm when used in conjunction with a 0.1µm cutter. A 0.1 µm cutter is in keeping with the specified part feature dimension of 0.1µm. Softer materials would require a higher spindle rpm, however 50,000 rpm can be established as minimum acceptable spindle speed.

A machine workspace which is 300mmx300mmx300mm is proposed. This machine travel range is in keeping with the travel range of most commercial CNC meso-milling desktop machines. This workspace would allow for fixturing multiple parts at once.

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[2] Capitalizing on the growing demand for Micro-milling. A Mold Maker's Guide. Page 5. www.cimatrontech.com

A feedstage resolution must be chosen to be smaller than the desired feed stage accuracy of 0.1 µm. A resolution of one order of magnitude less than the feed stage accuracy, or 10 nm is targeted as a machine specification. This resolution target will impose constraints on the CNC controller chosen as on the technology used to actuate the feed stages.

Once the spindle rpm has been established for a given application, the feed rate is a function of the spindle speed, the Chip Load and the number of cutter teeth according to the following formula:

Feed Rate [mm/s] = Spindle speed[rpm] x Number of teeth (Maximum of 2 flutes) x Chip Load [mm/tooth/rev]

Assuming carbon and alloy steels are used for roughing work, the Chip Load can be approximated as 0.0000254 mm/tooth/rev. Thus an approximate feed stage rate of 2.54 mm/s should be targeted.

Machine stiffness is an important contributor to surface roughness, part tolerance and the ability to machine hard materials. For a desktop CNC machine, the design of the closed loop load bearing path between the spindle and the workpiece must be optimized for stiffness. It has been suggested in some of the literature that a machine stiffness of 100N/µm should be targeted[3].

The above targeted machine specifications can be summarized as the following:

- A machine closed loop load stiffness of 100 N/µm.

[3] Luo, X., Cheng, K. Webb, D., Wardle, F. Design of ultraprecision machine tools with applications to manufacture of miniature and micro components. Journal of Materials Processing Technology Vol. 167 (2005) p.521.

1. A spindle runout of 0.8µm

2. A minimum spindle rpm of 50,000

3. A feed stage positional accuracy of 0.1µm

4. A feed stage assembly resolution (actuator, encoder, and controller) of 10 nm

5. A feed stage feed rate of 2.54mm/s

6. A workspace of 300mmx300mmx300mm

12.3 Development of Concept Selection Criteria.

The above machine specifications are targets which would guide the detailed engineering of individual machine concepts. In order to determine a design direction, and without realizing a detailed design of each engineering concept which would result in exact and comparable machine specifications, some concept selection criteria have to be developed which would encapsulate the engineering choices imposed by each concept. The selection criteria are similar to Pugh's method of concept selection and will quantify the designs based mostly on intangible criteria.[4]

These concept selection criteria can be summarized as:

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[4] Benhabib, Beno. Manufacturing: Design, Production, Automation and Integration. CRC Press. Boca Raton. 2003, p51. Pp589

1. Meso-milling machine must have a size which can fit on a desktop.

2. Machine must maximize stiffness and accuracy while maintaining a suitable meso-milling workspace.

3. Machine must have 6 spatial degrees of freedom, with a motion pattern suitable for machining 3D sculpted surfaces. A motion pattern [5] can be interpreted as the distribution of *m* mobility (ie. *m* number of working axis) within the workspace. An ideal workspace would have a uniform mobility of 6 which would include 3 translational axes and 3 rotational axes. The workspace created solely by 3 translational axes is referred to as 6 spatial degrees of freedom in this work.

4. Machine must minimize vibration of the workpiece and the tool when operating.

5. Machine must be easy to control.

6. For a given motion pattern, the machine must minimize the number of actuators required to control the machine.

7. The machine must include the potential for reconfigurability and hence have the possibility of including redundant machine axes.

The first and second criteria satisfy a need as determined by the above market evaluation: by creating a small desktop machine with improved accuracy, small and medium-sized machining enterprises with modest overhead, will have access to advanced CNC meso-milling technology.

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[5] Xianwen, K, Gosselin, Clement. Type Synthesis of Parallel Mechanisms. Berlin, New York. Springer 2007. Pp272.

The third criterion anticipates the ever-growing need to produce meso-scaled 3D mechanical parts.

The fourth criterion is required in order to produce meso-scaled parts with tight tolerances and a high quality surface finish.

The fifth criterion relates to the ease of use of the machine and to the ability to generate consistently and repeatedly highly accurate parts.

The sixth criterion determines how efficiently actuation is deployed in order to generate the tool path.

The seventh criterion, the potential number of redundant axes, is a measure of the machine flexibility. This criterion ensures that the machine can optimize an object function which may include accuracy, cycle time, and stiffness among others.

12.4 Parallel Kinematic Machines as a Design Direction.

Almost all meso-scaled milling machines currently offered to the marketplace today are serial machines. In other words, one feed-stage is added serially onto another stage. In order to increase the degree of the motion space, additional axes are added to the standard 3 axes required to create a 6 degree of freedom workspace. As a result of this choice of configuration, the errors from each stage are additive.

Since improving the accuracy and stiffness of the meso-scaled machine has been determined to be one of the main selection criteria for new concepts, developing different parallel kinematic mechanisms that would fit on a desktop is a promising direction to explore.

Parallel Kinematic Mechanisms (PKM) consists of closed loop chains which are in parallel between a base and a moving platform. The advantages of this family of mechanisms include increased accuracy, improved stiffness, and reduced dynamic weight.

The increased accuracy of PKMs is because the individual errors from each actuator are no longer additive, but are proportional to the largest error which occurs in any one of the parallel actuators (stages). The improved stiffness results from the additive stiffness of the many parallel kinematic chains, and the reduced dynamic weight is a consequence of feed stages no longer being stacked one upon the other.

Along with developing concepts based on PKMs, hybrid machine concepts can also be explored with a view to satisfying all of the concept selection criteria delineated above. A hybrid mechanism would consist of a PKM along with one or more serial stages included in the machine. Incorporating criteria No 3, 4 and 7 into a machine concept may thus be facilitated.

Currently, developing effective tools to choose the appropriate kinematic topology for a given PKM application is a matter of ongoing research within academia. However, in recent years, some authors, including [3], have formalized a method for synthesizing parallel mechanism. These methods include the application of screw theory, along with the synthesis of kinematic chains using some compositional chain sequences derived from screw theory.

While their work will be referenced when developing some new PKM concepts in the following sections of this thesis, mathematically formalizing the kinematics of each concept is beyond the scope of this work.

While performing a kinematic analysis of their topology is a worthwhile endeavour which merits more extensive study, existing Parallel Kinematic Mechanism can be evaluated for use in this new meso-milling application, using the concept selection criteria which I have elaborated in the previous section. This analysis would serve as a good preparatory step for future kinematic analysis. The following sections will describe the advantages and disadvantages of some of the significant PKM mechanisms which can be found in the machining industry as well as can be found in other applications such as robotic manipulators.

12.4.1 Delta Robot Strengths and Weaknesses.

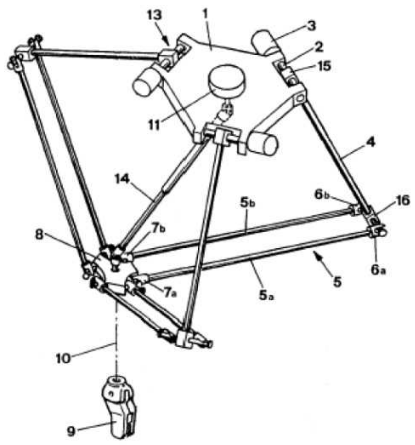

Fig. 1 Schematic of the Delta robot (from US patent No. 4,976,582)

The Delta Robot uses the principle of parallelograms in order to maintain an output link parallel to an input link. In this manner, the Delta Robot is capable of translational motion in the x, y, and z –direction. The Delta Robot also includes a fourth telescopic link which connects a swivel joint on the base to a manipulator on the moving platform. In this way, the manipulator can twist due to torque imparted to a swivel stage mounted on the base. The Delta Robot can be actuated by powering the revolute joints at the input of the parallelogram, or by providing linear actuation to the input linkage (arm) attached to each parallelogram[6].

Evaluating the Delta Robot according to the above concept selection criteria yields the following:

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[6] Bonev, I. , Delta Parallel Robot- The Story of Success. Para*ll*eMIC, www.parallemic.com

Criterion 1. The Meso-milling machine must have a size which fits on a desktop: The Delta Robots come in several sizes, however those which are used in the packaging industry have an overall dimension for the sum of the arm and parallelogram equal to less than 800mm.[7] This overall dimension is in the range which would fit on a desktop and thus the criteria is satisfied.

Criterion 2. The Machine must maximize stiffness and accuracy while maintaining a suitable meso-milling workspace.

The workspace for a Delta Robot which has an overall dimension of 800mm, is a cylindrical workspace which is 1 m in diameter and 0.2 m high. The mechanism can be used to pick and place light objects ranging from 10g. to 1 kg. Because of the low mass of the linkages, the moving platform can achieve accelerations of 12Gs. Precise data on the mechanism's accuracy is unknown, however larger versions of the Delta Robot are used in surgical applications which require a high degree of precision and accuracy. Therefore it is likely that the mechanism could be adapted to a meso-milling application. The use of six struts in the parallelogram would imply a high degree of stiffness for a given weight. It can be concluded that Criterion 2 is met by this mechanism.

Criterion 3. Machine must have 6 spatial degrees of freedom, with a motion pattern which is suitable for machining 3D sculpted surfaces.

The Delta Robot as 6 degrees of freedom since it provides translational motion in the X-Y and Z direction. By adding a swivel stage in serial to the base and the moving platform, a 4th axis can also be imparted to a manipulator on the moving platform. However, the mechanism lacks the

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7 Bonev, I. , Delta Parallel Robot- The Story of Success. Para*ll*eMIC, www.parallemic.com

ability to provide a tilting axis for 5 axes machining. Moreover, by adding a 4^{th} serial axes, the mechanism is no longer a strict PKM but a hybrid mechanism which may suffer from additive positional errors and additional dynamic weight. Thus Criterion 3 is not met by this mechanism.

Criterion 4. Machine must minimize vibration of the tool and workpiece when operating.

In either method of actuating the Delta robot, actuated revolute inputs to the parallelogram or linear motors attached to the input arms, the actuators are not mounted on the base of the mechanism. Therefore, it is more probable that the actuators could excite a natural frequency of one of these slender parallel links, especially if a larger mass such as a machining spindle is attached to the moving platform. Studies, of different PKMSs, have compared the frequency response and modal analysis of the parallel closed kinematic chains and they have concluded that the general vibrations of these chains are the predominant mode of vibration for the mechanism but with low amplitude and phase shift, and thus they usually have a negligible influence on the cutting process.[8] However vibrations of the kinematic chains can seriously affect the control of these actuators. If the actuators were mounted on a more substantial base, it would be less likely that they would transmit vibrations into the mechanism, or suffer control difficulties. It can be concluded that Criterion 4 may not be met in by this mechanism.

Criterion 5. Machine must be easy to control.

Closed loop control of this mechanism can be achieved by placing linear encoders or rotary encoders, depending on the method of actuation, on each of the actuators. Since the mechanism only has translational motion in the X, Y and Z directions, outer loop control of the moving

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[8] Weck, M., Staimer, D. Parallel Kinematic Machine Tools-Current State and Future Potentials. Manufacturing Technology. Vol.51. Issue 2, 2002, p677

platform could be achieved through a photo-detector array, an ultrasonic array, or a machine vision system. It can be conclude that Criterion 5 is met by this mechanism.

Criterion 6. For a given motion pattern, the machine must minimize the number of actuators required to control the machine.

This mechanism requires 3 actuators to control the X, Y and Z-directions along with a rotary stage to motivate the swivel axis. Therefore 4 independent actuators are required to control this mechanism. This number of actuators does not differ from the amount required to control a conventional serial 4-axis CNC machine. It can be concluded that Criterion 6 is met by this mechanism.

Criterion 7. The machine must include the potential for reconfigurability and hence have the possibility of including redundant machine axes.

In order for this criteria to be met the parallel mechanism must incorporate 5 machining axes: 3 translational (X,Y, Z-direction), 1 swivel axis and 1 tilt axis. Redundancy is then achieved by adding one or more serial stages to this parallel mechanism. Since this PKM only offers 3 machining axes, Criterion 7 is not met.

Evaluating the Delta Robot according to the concept selection criteria, reveals that Criteria 3, 4 and 7 are not met by this mechanism.

12.4.2 Hexapod Strengths and Weaknesses.

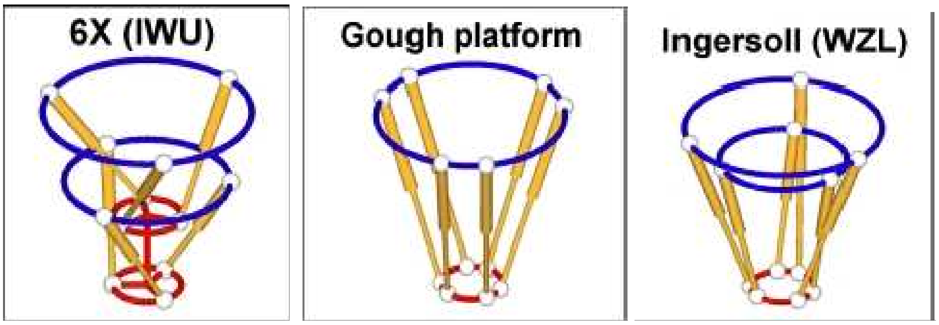

Fig 2. Design Variants of a Hexapod[9]

Hexapods have been used since the mid 1990s in the creation of macro-scaled CNC milling machines. As the above figure illustrates, there are many variations which are commonly referred to as hexapods, but all of them have some common characteristics. They feature six legs which are suspended from a base, using spherical or universal joints. Spherical or universal joints are also used to connect the legs to the moving platform. As innovation over serial-staged CNC milling machines, hexapods were chosen because the tracking errors and runout errors from each stage do not add up as they do in conventional machines. Moreover, since hexapods have six legs, they are very stiff, and have very stable platforms. The most commonly cited disadvantage to hexapods are their very small workspace.

Evaluating the hexapod according to our concept selection criteria yields the following:

Criterion 1. The Meso-milling machine must have a size which fits on a desktop:

For a given sized workspace, hexapods require a very large footprint. For example, there are commercially available micro-scaled hexapods which have a workspace of 50 mm in the X and

[9] Blumlein, W. J., The Hexapod. Maschine + werkzeug October 1999.p3

Y-directions, and 25 mm in Z-directions. The overall footprint of this hexapod is a cylinder of Ø350mm by 330 mm in height.[10] If the desired workspace of 300mmx300mmx300mm is required then the machine would necessitate a footprint of approximately 4.2mx4.0m. This machine footprint is larger than would fit on a desktop. In order to use a hexapod and fit it to a desktop, some compromises to the machine workspace would be required. It can be that Criterion 1 is satisfied to a lesser degree by this mechanism compared to the Delta Robot.

Criterion 2. The Machine must maximize stiffness and accuracy while maintaining a suitable meso-milling workspace.

The same miniature hexapod used as reference while evaluating Criterion 1 can also be used to evaluate Criterion2. This machine has a repeatability of 1µm and a stiffness of 100 N/µm in the Z-direction, but its stiffness is only 3N/µm in the X and Y-direction. Moreover the workspace travel in the X, Y, and Z directions are not independent as the position of travel in one direction may adversely affect how much travel is left in the other directions. It is thus shown that Criterion 2 is satisfied to a lesser degree by this mechanism compared to the Delta Robot.

Criterion 3. Machine must have 6 spatial degrees of freedom, with a motion pattern which is suitable for machining 3D sculpted surfaces.

The hexapod has six spatial degrees of freedom and a motion pattern which is equivalent to 5 axis of motion. This motion pattern however is not uniform over the entire travel in the X,Y and Z-direction. Moreover, the swivel and tilt axis, A and B axis, can typically only reach a maximum of ±30° and ±15° respectively. It is thus evident that the criterion for machining 3D

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[10] M-850 Hexapod 6-Axis Positioning System datasheet. PI Nano Precision. www.PI.ws

sculpted surfaces is not fully met by this mechanism, however, Criterion 3 is more fully satisfied by the Hexapod than it is by the Delta Robot.

Criterion 4. Machine must minimize vibration of the tool and workpiece when operating.

The actuators on the hexapod are six linear motors attached to the six legs. Similar to the Delta Robot, because the actuators are not mounted on the base of the mechanism, they risk exciting a natural frequency of one of the legs of the hexapod during operation. For example on the previous referenced miniature hexapod datasheet, this sample mechanism as a natural frequency of 500Hz in the Z-direction, but it only has a natural frequency of 90Hz in X and Y-directions. Therefore, it is more probable that the actuators could excite a natural frequency of one of these slender parallel links in the X or Y direction, especially if a larger mass such as a machining spindle. Such vibrations could result in significant dimensional errors, of a rough surface finish.

Criterion 5. Machine must be easy to control.

The hexapod linear motors or lead screws can be fitted with linear or rotary encoders respectively. As an outer loop control, it is common to mount additional central struts to the moving platform which are used to determine the final X, Y and Z position of a central point on the moving platform. While many people have commented that the direct and inverse kinematics of a hexapod are non-intuitive, there exists today many powerful controllers with realtime ability which routinely compute these kinematics. Thus Criterion 5 is met by the hexapod mechanism.

Criterion 6. For a given motion pattern, the machine must minimize the number of actuators required to control the machine.

With the hexapod, for a motion space equivalent to 5 machining axis, six actuators are required to motivate this mechanism. This number is more than would be required by a conventional serial stage milling machine with 5 axis. Thus Criterion 6 is not met by this mechanism.

Criterion 7. The machine must include the potential for reconfigurability and hence have the possibility of including redundant machine axes.

The hexapod parallel mechanism has a motion pattern of 5 machining axes. Thus a redundant hybrid mechanism can be created by adding serial stages for swivel and tilt to the machine. However, this redundancy is over a limited range since the parallel mechanism offers a swivel and tilt mechanism over a range of ±30° and ±15° respectively. It is thus shown that Criterion 7 is satisfied by this mechanism, but only over a limited range of workspace.

Evaluating the Hexapod according to the concept selection criteria, reveals that Criteria 1, 4 and 6 are not met by this machine, and Criteria 3 and 7 are not fully satisfied by this mechanism.

12.4.3 The Pentapod Strengths and Weaknesses

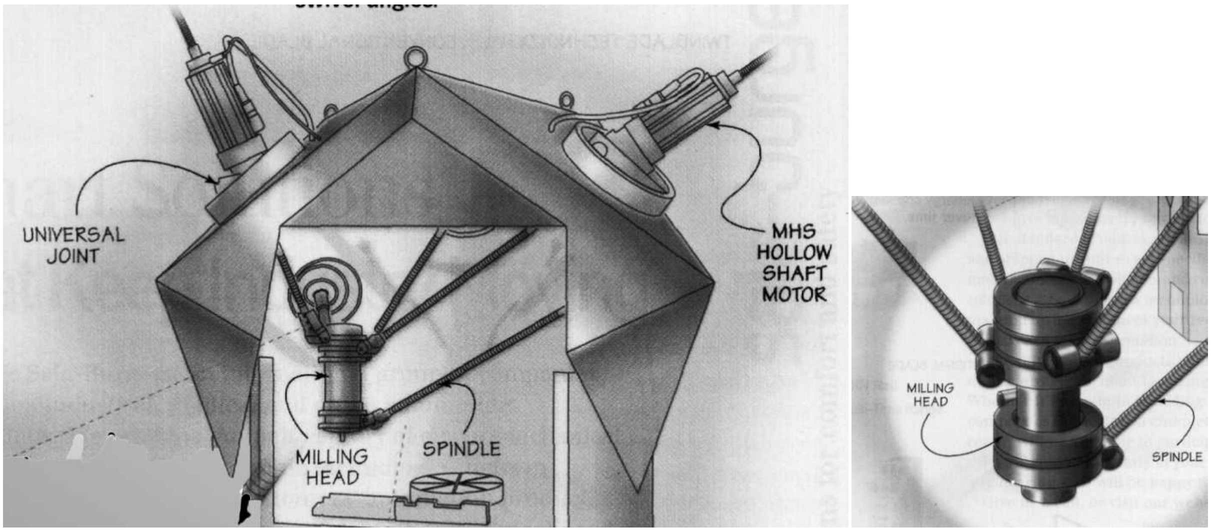

Fig 3. Metrom's Pentapod Milling Center[11]

The pentapod is intended to increase the ratio of workspace to build volume compared to a hexapod. Moreover, a pentapod can tilt ±90° while a hexapod can typically reach only ±15° of tilt. As illustrated in the above conceptual drawing by the designer Michael Schwaar, the five struts on the pentapod are staggered along the length of the moving platform, and the joints connecting the struts to the moving platform consists of double revolute joints. The intended advantage to staggering the joints and using double revolute joints is to increase the stiffness of the mechanism when the head is tilted away from the vertical.

Criterion 1. The Meso-milling machine must have a size which fits on a desktop:

Because the pentapod is more efficient in its use of build volume compared to a hexapod mechanism, this mechanism more readily meets Criterion 1, compared with a hexapod. The

[11] Schwaar, M., Stiff pentapod, Design News, Jul.22, 2002, pg41

machine has a footprint of 2.2mx1.9mx2.3m and has a total workspace of 800mx800mx500m. By extrapolating a rough approximation of the footprint size for a workspace of 300mmx300mmx300mm would be 825mmx712mmx1380mm. Therefore the pentapod satisfies Criterion 1 more than the hexapod does.

Criterion 2. The Machine must maximize stiffness and accuracy while maintaining a suitable meso-milling workspace.

The macro-scaled pentapod milling machine has an accuracy of 10 µm and a repeatability of 3µm. It is expected that accuracy would improve if the existing technology was used on the meso-scale. The pentapod mechanism at the macro scale has a accuracy which is roughly on par with most machines that use a Hexapod configuration. Moreover, the machine was design intent was to improve stiffness of the machine's range of motion pattern compared to a hexapod. Because the struts are offset, this mechanism has the potential depending on its design execution to be stiffer than a hexapod. Therefore the pentapod satisfies Criterion 2 more than the hexapod does.

Criterion 3. Machine must have 6 spatial degrees of freedom, with a motion pattern which is suitable for machining 3D sculpted surfaces.

The pentapod mechanism offers a completed 5 sided machining, and has 5 axis machining capability. The A-axis (swivel) is advertized as ±25° and the B-axis (tilt) is ±90°. Therefore this mechanism is suitable for machining 3D sculpted surfaces and satisfies Criteria 3 over a larger range of the workspace, compared to the hexapod.

Criterion 4. Machine must minimize vibration of the tool and workpiece when operating.

The pentapod relies on hollow shaft electric motors for actuation. These hollow shafts are attached to the base of the machine using universal joints. Figure 3 shows how the hollow shaft acts as lead screw to move a fixed rod length in and out. Moreover the figure shows how the universal joint mounted at the base serves to modify the rod angle depending on the desired tool path. Because the actuators are mounted very close to the base of the machine, the actuators would be less prone to exciting a modal response from the mechanism, and would thus be easier to control using a servo feedback loop. Therefore the pentapod satisfies Criterion 4 more than the hexapod does.

Criterion 5. Machine must be easy to control.

The Metrom Pentapod controller uses a conventional coordinate system, and computes the inverse kinematics for the actuators. Because the machine uses hollow shafts, it is expected that conventional rotary encoders could be used and could be mounted right at the base of the machine, instead of between a conventional motor and a leadscrew. In this way the sensor would be less prone to vibration, could be used to its highest potential and would thus provide the highest possible accuracy. Therefore this mechanism satisfies Criterion5 more fully than does the hexapod.

Criterion 6. For a given motion pattern, the machine must minimize the number of actuators required to control the machine.

The pentapod requires 5 actuators in order to provide a 6 degree of freedom workspace and a motion pattern that is equivalent to 5 axis: a smaller number of actuators are used to provide a more extensive motion pattern for a tool compared to the hexapod. Therefore, this mechanism satisfies Criterion 6 more than does the hexapod.

Criterion 7. The machine must include the potential for reconfigurability and hence have the possibility of including redundant machine axes.

The pentapod parallel mechanism has a motion pattern of 5 machining axes. Thus a redundant hybrid mechanism can be created by adding serial stages for swivel and tilt to the machine.

Moreover due to the larger workspace provided by its A and B axes, this mechanism provides redundancy over a more extensive range. Therefore, this mechanism satisfies Criterion 7 more fully than does the hexapod.

In summary the pentapod meets all of the concept selection criteria, and satisfies a number of criteria more fully than does the hexapod.

12.4.4 The Eclipse Strength and Weaknesses

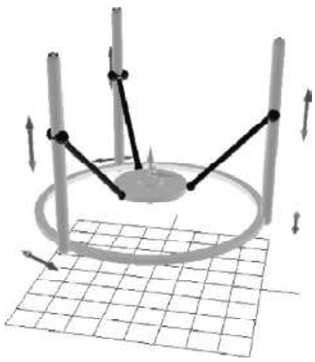

Fig.4 The Eclipse Mechanism[12]

The Eclipse uses rods of fixed length which are mounted to the moving platform using spherical joints. The opposing ends of each rod are attached to the base by connecting a revolute joint to two prismatic joints. Starting from the base, the first prismatic slider travels along a circular ring, while the second prismatic slider travels along a vertical axis. This mechanism is capable of tilting the moving platform by ±90°: in order to do so, two of the vertical legs are moved along the circular ring until all three legs are positioned within an arc which is less than 180°.

Criterion 1. The Meso-milling machine must have a size which fits on a desktop:

The Eclipse-RP 5 axis rapid prototyping machine is manufactured by Daeyoung Machinery. The machine has a cylindrical workspace of Ø170mmx150mm in height. This workspace is less than the targeted workspace for the desktop meso-milling machine of 300mmx300mmx300mm. However the machine already has a footprint of 3.5mx1.9m. Thus for the required workspace, this machine does not fit on a desktop and Criterion 1 is not met.

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[12] Kim, J., Park, F.C. Direct Kinematic Analysis of 3-RS parallel mechanisms. Mechanism and Machine Theory Vol.36 2001, pg 1122.

Criterion 2. The Machine must maximize stiffness and accuracy while maintaining a suitable meso-milling workspace.

The stiffness of this machine varies considerably depending on the position of the moving platform within its workspace, and depending upon the angle of tilt. In order to create adequate stiffness when the spindle head is tilted, 2 redundant actuators have to be added to the mechanism, and a total of 8 actuators are required to operate this mechanism. Therefore, in its simplest form, the eclipse mechanism does not meet Criterion 2.

Criterion 3. Machine must have 6 spatial degrees of freedom, with a motion pattern which is suitable for machining 3D sculpted surfaces.

The Eclipse has a motion pattern equivalent to 5 axes, in a 6 spatial degree of freedom workspace. Therefore the eclipse is suitable for 3D sculpted machining. Moreover the mechanism has a tilt range of ±90° and a swivel range of 360°. Therefore Criterion 3 is met by this mechanism and is more fully satisfied by this mechanism compared to the hexapod.

Criterion 4. Machine must minimize vibration of the tool and workpiece when operating.

The active joints on this mechanism are the 6 prismatic joints (2 joints per leg). Since these actuators are mounted near the base of the mechanism, it is less likely that a modal frequency of the mechanism will be excited, or that vibration will be imparted to the moving platform or the actuators themselves. Therefore this mechanism would be less sensitive to errors introduced due to vibration. Criterion 4 is thus met by this mechanism.

Criterion 5. Machine must be easy to control.

The eclipse poses some unique challenges in instrumentation. Because the first prismatic slider moves along a circular rail, a linear encoder must be used, but linear encoders are not normally fitted to a circular path. Therefore achieving the desired positional accuracy with this mechanism poses greater challenges. Moreover since the circular rail is a closed path, care must be taken when instrumenting a home position, as one moving platform position could have several possible inverse kinematic solutions. Therefore in order to calibrate the machine, one must ensure that the same inverse kinematic solution is always used. Therefore, this mechanism would be more difficult to control than the hexapod or the pentapod, and hence Criterion 5 is less satisfied by this mechanism.

Criterion 6. For a given motion pattern, the machine must minimize the number of actuators required to control the machine.

As previously stated, this mechanism requires 8 actuators, 2 of which are redundant, to operate and thus the number of actuators required to achieve 5-axis machining is not optimized. Therefore Criterion 6 is not met by this mechanism.

Criterion 7. The machine must include the potential for reconfigurability and hence have the possibility of including redundant machine axes.

The eclipse parallel mechanism has a motion pattern of 5 machining axes. Thus a redundant hybrid mechanism can be created by adding serial stages for swivel and tilt to the machine. Moreover due to the larger workspace provided by its A and B axes, this mechanism provides redundancy over a more extensive range. Therefore, this mechanism satisfies Criterion 7 more fully than does the hexapod but is on par with the pentapod.

In summary, criteria Nos 1, 2, and 6 are not met by this mechanism, while criterion No 5 is less satisfied by the mechanism compared to the pentapod and hexapod. The eclipse mechanism satisfies Criteria Nos 3 and 6 more fully than the hexapod does.

Evaluation of these 4 Commercialized Mechanisms according to Pugh's methodology

Selection Criteria	Reference Concept: The Pentapod	The Delta Robot	The Hexapod	The Eclipse
No 1		+	-	-
No 2		-	+	-
No 3		-	-	Same
No 4		-	-	Same
No 5		Same	-	-
No 6		-	-	-
No 7		-	-	Same
∑ (+)		1	1	0
∑(-)		5	6	4
∑(same)		1	0	3

According to Pugh's method, the designer iteratively identifies one of the concepts as the reference concept, and each of the mechanism are compared to the reference concept using the concept selection criteria; the resulting best concept is identified as the new reference concept. The iterations are stopped once the best concept does not change.

The above table is the result of this process, with the pentapod being identified as the existing mechanism which most closely suits the requirements for a new meso-milling desktop machine. Some of the key features which make the pentapod desirable are its efficient workspace, its efficient motion space, its fixed length rods which minimize vibration, and the choice of joint design which optimizes stiffness.

12.5 Constraints in the Design of Existing Parallel Kinematic Machines (PKM)

12.5.1 Types of Joints (Prismatic, Revolute, Universal and Spherical)

The above joint types, listed in order of ascending degrees of freedom, in combination with the number of rigid body links, are used to create the kinematic chains which make up a parallel kinematic mechanism. A kinematic loop would consist of the chain which makes up one leg, starting from, and including the base, up to and including the moving platform, followed by a returning virtual chain. The virtual chain is a symbolic representation of the leg, made up from the compositional joints which effectively summarize the motion pattern created by the leg's kinematic chain. In other words, while kinematic chains often require additional links and joints due to the physical constraints and limitations of the joints, a virtual chain composed of basic building blocks can often effectively summarize the motion created by the leg's kinematic chain. For example the hexapod leg can be described by the virtual chain RRPS (revolute, revolute, prismatic, and spherical

These basic building blocks are the prismatic and revolute joint and their combination. For example a universal joint is composed of two revolute joints whose axis are perpendicular to each other, while a spherical joint consists of three revolute joints whose axis are perpendicular to each other. Spherical joints are the joints with the highest degree of freedom (3 axes), however they have a reduced range of motion (typically ±15°), therefore due to these physical constraints, it is sometimes necessary to create a more elaborate mechanism consisting of three revolute joints. Moreover, spherical joints are prone to misalignment which can lead to loss of motion pattern or loss of accuracy. Recently some new joints, such as the Omni wrist have been created which provide ±90° of rotation in 2 degrees of freedom, while offering improved alignment. Other companies such as INA and Hephaist Seiko have been working on increasing the range of motion for spherical joints to between ±30° and ±45°.[13]

As a general rule, whenever the joint's mobility increases, there is a tradeoff in the stiffness of the joint. Therefore it is sometimes better to use joints with a mobility of one degree to create compositional units.

The prismatic joint, combined with a revolute chain, create a well defined compositional unit, or building block, whose motion pattern can be described using screw theory [1]. The principle of a screw system in a kinematic chain is that the "twist" imparted to a rigid body link is opposed by the "wrench" imparted by the other links in the kinematic chains. Thus mathematically, a wrench is the reciprocal of the twist. The wrenches from each kinematic link can be combined using vector algebra and linear algebra. In this work, a wrench will be represented by ζ and a twist will be represented by ξ. A wrench of infinite pitch will be represented by ζ_∞ (translational axis) and a wrench of zero pitch will be represented by $\zeta_{0.}$ A compositional unit consisting of a parallel and revolute joint can be summarized by 2 degrees of freedom or $2\text{-}\zeta_\infty$ - $2\zeta_0$ –system.

12.5.2 Number of Active and Passive Joints.

The number of active joints is the minimum number of joints which, when blocked, will prevent all motion of the parallel mechanism. Therefore if a mechanism has a mobility of 6, then as a rule of thumb, 6 joints will need to be blocked in order to prevent motion. There are exceptions

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[13] Merlet, J.-P. Parallel Robots, Springer, Second Edition p30.

to this rule, particularly if the joint to be blocked as more than one degree of freedom, or if there is some linear dependence between the kinematic chains (legs).

12.5.3 Discussion of the resulting workspace

In the previous section, as a recall, a motion pattern is interpreted as the distribution of *m* mobility (or *m* number of working axes) over the workspace. Any parallel mechanism concept which is intended for machining sculpted surfaces should thus be designed in order to have a mobility of 6 over the entire workspace. If a mobility of 6 is not achievable, than the design should target a uniform mobility of 5, with the rotation axis which is co-axial with the tool removed as superfluous.

The mobility of a kinematic chain is defined according to the Chebychev-Grubler-Kutzbach equation:

$$\mathcal{F}_j = d_j(n_j - g_j - 1) + \sum f_i \quad (1.1)$$

Where f_i is the number of degrees of freedom for the ith joint, d_j is the number of independent constraint equations in the kinematic chain, n_j is the number of solid body links, and g_j is the number of joints in the kinematic chain.

According to [1], the mobility of the mechanism can be determined by:

- Calculate the connectivity $\mathcal{C}$ of the moving platform in the single loop virtual chain:

$$\mathcal{F}_j = f_j - \mathcal{C} \quad (1.2)$$

- Calculating the order of the wrench system c_j for the kinematic chain

  a. $C_j = 6 - c_j$ (1.3)

- Calculate the redundant Degree of Freedom (DOF) for each leg j

$R_j = \sum f_i - 6 + c_j$ (1.4)

- Formulate the number of overconstraints in the Parallel Kinematic Mechanism

$\Delta = \sum c_j - c$ (1.5)

where c is the order of the wrench system of the Parallel Mechanism obtained from

c = 6 - C(moving platform connected between legs and virtual chains)

- Obtain the mobility of the mechanism $\mathcal{F}$ by solving:

  (1) $\sum c_j = 6 - \mathcal{F} + \Delta + \sum R_j$ (1.6)

12.6 PKM features to include in a new mechanism design

The above mechanisms and their constraints were analyzed in order to determine features which would be suitable for the incorporation in the synthesis of a new parallel kinematic mechanism. In summary some of the features which would be favored in a new mechanism design would include:

- Actuators which are mounted on the base of the machine.
- Solid body links which are of fixed length.
- The use of 1 DOF joints whenever possible in order to optimize stiffness and accuracy.
- A mechanism which maximizes mobility and targets a uniform mobility over the workspace.

12.7 Development and Discussion of Concept 1.

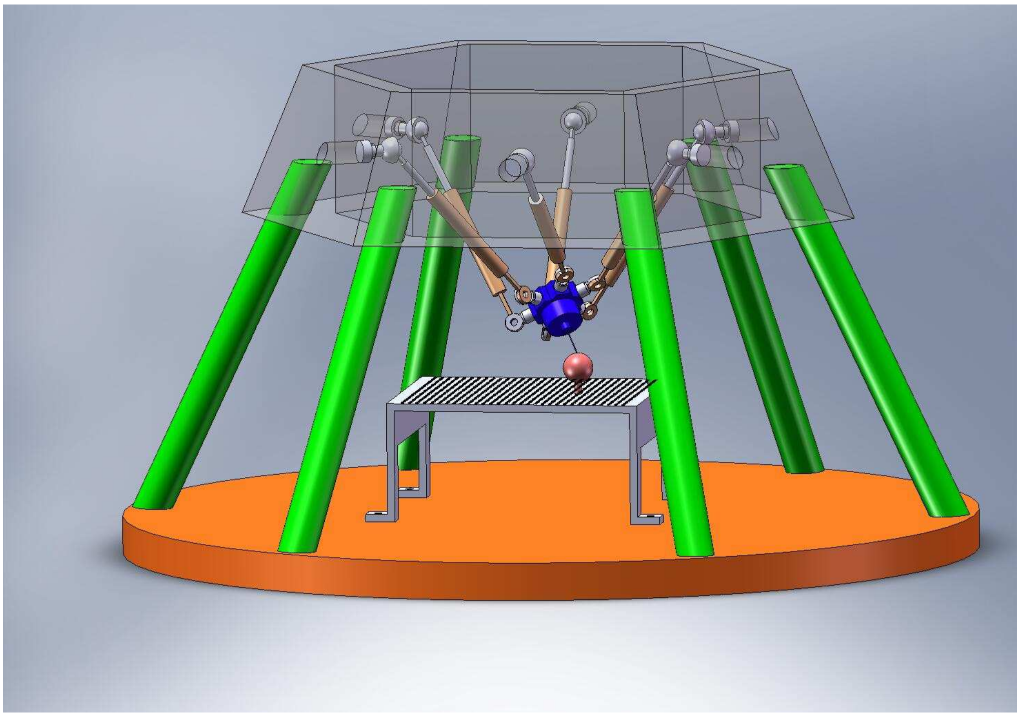


Fig.5 Concept 1 for a meso-scale milling machine

Concept 1 addresses a number of the issues which are important for meso-milling:

The machine structure is designed to enhance stiffness. The cast hexagonal ring is an enclosed structure which provides a very stiff base for mounting the parallel kinematic mechanism. Moreover the six leg mounts serve to provide a uniform stiff load path for transmitting the machining forces to the base of the machine. As a result, there are six closed force loops between the tool and the workpiece which serve to minimize bending, and hence deflection within the structure, since all the loads are carried in compression or tension. Likewise the six legs of the parallel kinematic mechanism serve to enhance the stiffness of this mechanism which will result in a higher modal frequencies and thus less vibration of the tool.

The mobility of the mechanism is 6, and thus the mechanism has an appropriate number of working axes for machining 3D sculpted mechanical parts. For a review of the mobility calculations for this mechanism, please refer to appendix B.

The machine relies on simple, repetitive mechanical components which will result in lower costs to manufacture.

The evaluation of this machine concept can be formalized according to the previously elaborated concept selection criteria.

Criterion 1. The Meso-milling machine must have a size which fits on a desktop:

This concept, which is not at the stage of detailed- design execution has a platform diameter of 1150mm with a height of 650 mm. The six spatial dimension workspace of this machine concept is approximately 200mmX200mmX150mm. Thus this concept has a footprint which is slightly larger than current commercial desktop serial-stage CNC machines, and offers a workspace which is slightly smaller than current commercial serial-stage desktop CNC machines. Criterion 1 is satisfied by this concept.

Criterion 2. The Machine must maximize stiffness and accuracy while maintaining a suitable meso-milling workspace.

Given the similarities between this concept and standard Stewart Gough platforms, it is expected that this mechanism would have a stiffness and accuracy similar to that of the hexapod. Moreover, the design of the support structure of this machine would serve to enhance the stiffness of the mechanism. Knowing the exact stiffness and accuracy of this machine would require detailed design and execution. It is expected that Criterion 2 is satisfied by this mechanism.

Criterion 3. Machine must have 6 spatial degrees of freedom, with a motion pattern which is suitable for machining 3D sculpted surfaces.

Concept 1 has 6 spatial degrees of freedom and a mobility of 6 thus it is suitable for machining 3D sculpted surfaces. In order to ensure that the mobility of the mechanism is uniform across the workspace, detailed calculation of the kinematics of this mechanism would be required.

Criterion 4. Machine must minimize vibration of the tool and workpiece when operating.

While it is expected that the structure of this machine would be very stiff, and therefore have high modal excitation frequencies, a drawback to this mechanism is that the actuators would have to be mounted along each of the six prismatic joints which make up the mechanism's struts. Since these struts are in motion, the actuators would be prone to vibration, and, as explained previously, the mechanism could suffer from deterioration in control and accuracy. Therefore Criterion 4 is not met by this mechanism.

Criterion 5. Machine must be easy to control.

Given its similarities with the hexapod, it is expected that this mechanism would have comparable ease of control. Therefore it is expected that Criterion 5 is met by this mechanism.

Criterion 6. For a given motion pattern, the machine must minimize the number of actuators required to control the machine.

Six actuators are required to control this mechanism, and since this mechanism offers a mobility of 6, the number of actuators is minimized. Thus criterion 6 is met by this mechanism.

Criterion 7. The machine must include the potential for reconfigurability and hence have the possibility of including redundant machine axes.

As illustrated in Figure 6 attached below, the machine offers the possibility of including redundant serial stages for the A and B axis. Thus the machine has the potential for reconfigurability in which the selection of working axes are optimized for objective function which could include accuracy, stiffness, or cycle time.

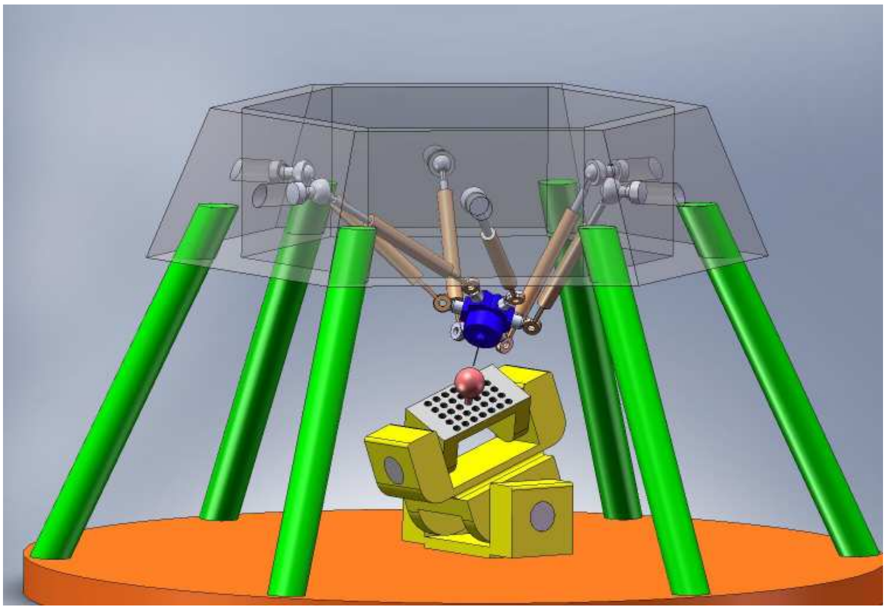
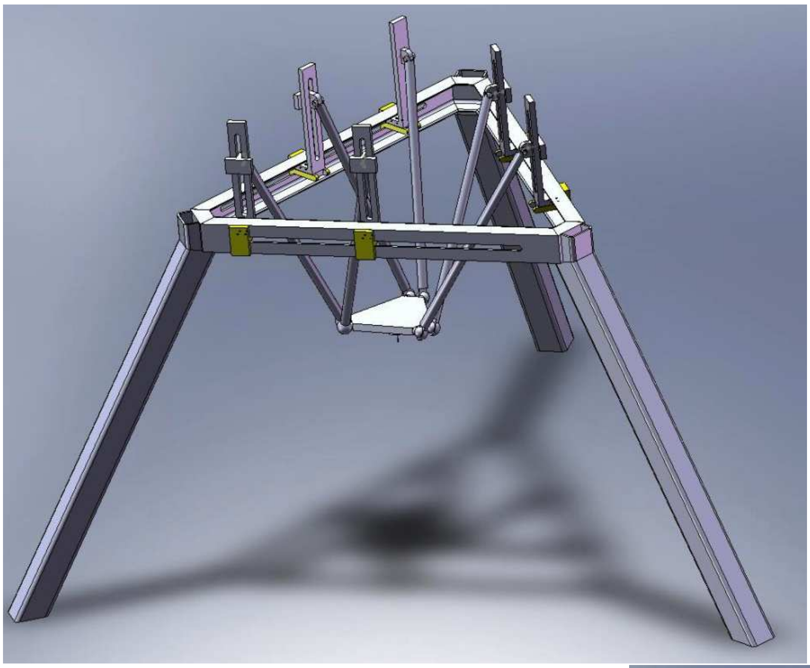


Fig 6. Concept 1 with redundant A and B axes.

In summary, while Concept 1 satisfies most concept selection criteria, a significant disadvantage of this mechanism is that Criterion 4 is not met by this mechanism.

12.8 Development and Discussion of Concept 2



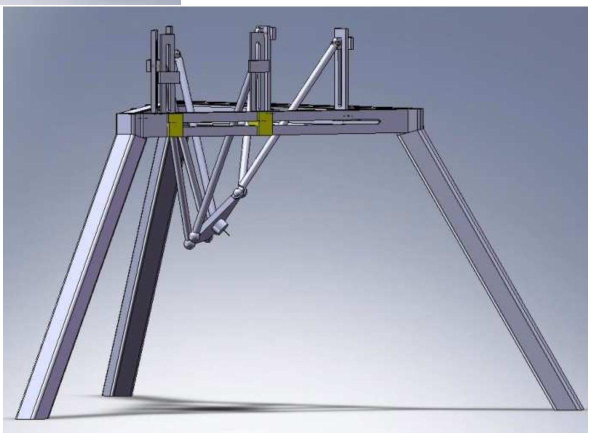


Fig 7. Concept 2 for a meso-milling machine.

Similar to Concept 1, this machine concept features an enclosed triangular base and structure which will enhance the stiffness of the mechanism. This structure could be a weldment, or it could be machined from raw stock steel. The mechanism features six solid rigid links of fixed length which are attached to a triangular moving platform. These six links will ensure a stiff mechanism which, depending on the design execution, will provide improved accuracy compared to meso-milling machine with serial stages.

The mobility of this mechanism is 6, and the calculations can be viewed in Appendix B.

Actuators, consisting of linear motors or inchworm drives could be used on the horizontal and/or vertical prismatic joints.

The application of the concept selection criteria to this concept can be summarized as follows:

Criterion 1. The Meso-milling machine must have a size which fits on a desktop:

As concepted, this machine has a footprint consisting of a isosceles triangular mechanism base of 1.06 m in side length (2.3 m at the machine's feet) by a height of 1.2 m. The workspace for this concept is approximately 400mmX400mmX150mm. While the exact dimensions of the footprint and the workspace of this machine will depend on the design executions, the dimensions above demonstrate that the machine could provide a workspace comparable to current commercial CNC meso-milling machines while fitting on a desktop. Therefore, Criterion 1 is met by this mechanism.

Criterion 2. The Machine must maximize stiffness and accuracy while maintaining a suitable meso-milling workspace.

Determination of the stiffness and accuracy of this machine will depend on the design execution of the structure, the mechanism and the actuators. However there are some basic features which are offer improved stiffness and accuracy, including the use of only 4 rigid links and 4 joints in one kinematic chain, the large number of single DOF joints and the use of 6 repetitive kinematic loops. Thus it is expected that Criterion 2 would be satisfied by this concept.

Criterion 3. Machine must have 6 spatial degrees of freedom, with a motion pattern which is suitable for machining 3D sculpted surfaces.

Concept 2 has 6 spatial degrees of freedom and a mobilityof 6 thus it is suitable for machining 3D sculpted surfaces. In order to ensure that the mobility of the mechanism is uniform across the workspace, detailed calculation of the kinematics of this mechanism would be required. It is expected that Criterion 3 is satisfied by this mechanism.

Criterion 4. Machine must minimize vibration of the tool and workpiece when operating.

Since the actuators are mounted near the base of the mechanism along the horizontal and/or vertical prismatic joints of this mechanism, it is expected that they would be less prone to vibration compared to Concept 1, and would thus offer improved control and accuracy. Therefore it is expected that Criterion 4 is met by this mechanism.

Criterion 5. Machine must be easy to control.

Simple linear encoders could be mounted along the triangular sides of the mechanism for closed loop control of the actuators. Given the ease of instrumentation, it is expected that this mechanism would be easy to control and would thus provide accurate positioning. It is expected that Criterion 5 would be met by this mechanism.

Criterion 6. For a given motion pattern, the machine must minimize the number of actuators required to control the machine.

This mechanism requires 6 actuators to operate this mechanism. The actuators would ideally be placed all on the horizontal prismatic joints, however there is a dependency between the 6th horizontal prismatic joint and the remaining 5 horizontal joints. Further investigations are necessary to determine why this dependency arises, although it is hypothesized that the triangular configuration of the mechanism's base creates this dependency. Because of this dependency, currently not all 6 active joints can be placed on the horizontal, so the 6th joint has to be on the vertical. Therefore it is expected that a minimum number of actuators are used, since for a mobility of 6, six actuators are used to control this mechanism. It is expected that Criterion 6 is met by this mechanism.

Criterion 7. The machine must include the potential for reconfigurability and hence have the possibility of including redundant machine axes.

Similar to Concept 1, this concept offers 6 working axes, therefore redundancy can be created by adding serial A and B stages to the base.

In summary Concept 2 fully meets all of the concept selection criteria, however, due the dependency of the 6th prismatic joint with the 5 other horizontal joints, the operation of this mechanism requires one vertical actuator, and may thus more be complicated and perhaps less intuitive than if all of the prismatic joints are mounted on one axis.

12.9 Development and Discussion of Concept 3

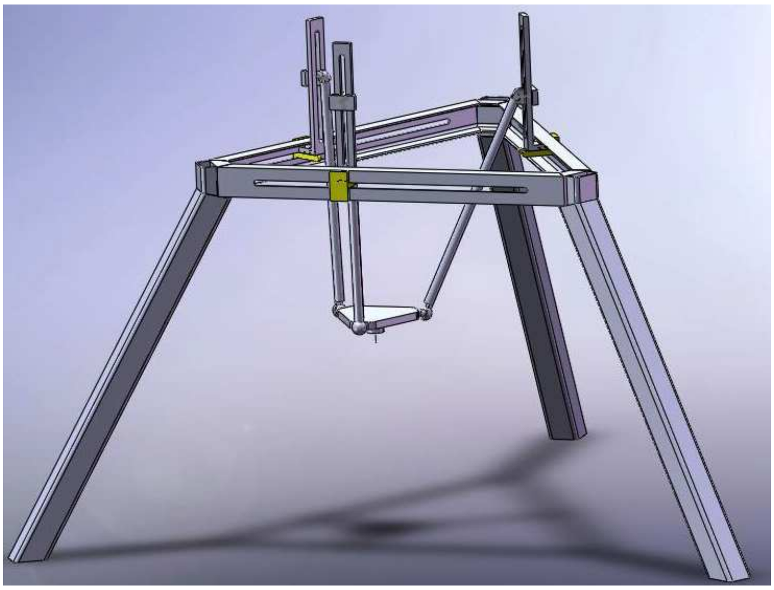


Fig.8 Concept 3 for a meso-milling machine

Concept 3 is similar to Concept 2 except there are 3 legs instead of 6 legs. The same number of actuators is required to motivate this mechanism, with 3 actuators along the horizontal prismatic joints and 3 actuators along the vertical prismatic joint.

Please refer to Appendix B, in order to review the mobility calculations for this mechanism.

All of the concept selection criteria are met by this mechanism, and the mechanism may be easier to operate than Concept 2, however, because only 3 legs are used in the parallel mechanism, the assembly may be less stiff than Concept 2.

12.10 Comparison and Evaluation of the Concepts.

Selection Criteria	Concept 3 (Reference)	Concept 1	Concept 2
No 1		+	(Same)
No 2		+	+
No 3		-	(Same)
No 4		-	(Same)
No 5		(Same)	-
No 6		-	(Same)
No 7		(Same)	(Same)
∑ (+)		2	1
∑(-)		3	1
∑(same)		2	5

Given the similar scores achieved by Concept 3 and Concept 2, the kinematics of each mechanism and their resulting workspace would have to be calculated in order to decide which mechanism is preferable. Concept 3 may be easier to control than Concept 2, however, the tradeoff is that Concept 3 may be less stiff than Concept1.

12.11 Future Initiatives- Further Concepts

Further concepts may be developed by exploring different geometries to use as a base for Concept 2 and 3: instead of an isosceles triangle, other geometries may provide a better workspace and motion pattern.

In addition, instead of using two prismatic joints in sequence, other mechanism concepts, similar to the Delta Robot, which rely on revolute joints should be investigated. Developing rotary actuators with high resolution that would fit on these joints could be a research initiative.

Finally, all 3 concepts described above rely on a least one spherical joint in their kinematic chain. Efforts should be directed at eliminating these joints if possible, by replacing them with two revolute joints in sequence (a universal joint) if possible, or by using three revolute joints in sequence if necessary.

13. Development and Implementation of a Numerical Controller for a Meso-Milling CNC Machine

As previously introduced, the design of open architecture CNC controllers from third party vendors has enabled many small to medium sized CNC machine builders to implement sophisticated controller algorithms in their machines, and has enabled them to differentiate their machines from their competitors, without incurring the significant research and development costs required to develop their own controller hardware. A machine builder can use the control algorithms which come as standard with the controller, or they can use high level programming languages and simulations to develop their own control algorithms and download these algorithms to the purchased controller.

13.1 Litterature review of existing controllers and control strategies

Control of CNC feed stages is provided by means of outputting a digital signal which is usually the feed velocity for an interpolated path. The signal is outputted as a DAC (Digital Analog Conversion) signal to the motor's amplifier or the motor amplifier may accept the digital signal and provide its own conversion when doing the motor's commutation.

In setting up a controller for use with a CNC machine, the controller designer and installer must first model the axis dynamics for the feed stage. These are the equations of state in the control algorithm and are determine by running motor "tuning" subroutines. In order to perform this tuning, the feedback loop from the servo drive can be used. For a stepper motor, simulated feedback is used in which the back emf from the motor bridge is used instead of an encoder. The axis dynamics will include the current amplifier gain, the motor torque constant, and the inertia of the stage. This inertia will include the inertia from the motor shaft along with that of the transmission device such as a leadscrew. The exact values of these parameters remain hidden from the person setting up the controller, rather the controller software tells the person when the reference signal outputted by the controller corresponds to the actual displacement of the motor.

Moreover, much of the machine designer's interaction with the controller is setting up the parameters involved with the motion program, including the interpolation procedures which will be used. If he or she so chooses, the machine designer does not have to concern himself with designing the control algorithms which will be used for real-time operation of the feed stages. Most controllers come standard with a proportional derivative (PD) or proportional integral derivative (PID) algorithms.

However, there is a whole body of academic research which has focused on developing control algorithms specifically for CNC feed stages. The machine designer who undertakes to learn these control strategies has the potential to construct a superior CNC machine, particularly, in this era of open architecture controllers where many controller hardware limitations are removed.

Some of the controllers developed in Academia over the years, and which are intended specifically for CNC feed stages include:

1. The development of feedforward controller blocks in order that there is no phase lag between the reference output and the actual output. In this way contour error is reduced even if the controller has limited bandwidth.

2. The development of elaborate friction compensation algorithms to reduce errors which arise when there is a change in direction.

3. The development of Disturbance Observer (DOB) controllers for removing measurement uncertainty.

4. The development of sliding mode controllers, specifically Adaptive Robust Controllers (ARC) which are made robust or insensitive to small disturbances which can arise due to trajectory discontinuities, instrumentation error, or high frequency noise.

5. The application of non-linear control algorithms for use with feed stages in order to reduce processing time.

13.1.1 Resolution of Existing Commercial Machines

A CNC machine's resolution is dependent of many factors including the resolution of the interpolated tool path which is influenced by the controller's processing ability, the resolution of the encoder's which will determine the measurement accuracy of the feed-stage, the pitch and backlash of the stage's leadscrew (or other type of mechanical transmission) which will determine how much lost motion there is in a feedstage.

These individual factors will combine to determine a CNC milling machine's resolution which can be defined as the smallest increment in commanded displacement (or reference output) for which there is a corresponding actual displacement of the feed-stage.

Currently most commercial meso-milling CNC machines advertize a resolution which has a value that is normally one or two orders of magnitude less than the advertized accuracy of the machine. This resolution can range from 1 nm for a high-end machine to a few microns for a low-end desktop machine.

While established standards exist for measuring the accuracy and the repeatability of a CNC machine tool, there is no convention for reporting the resolution of a machine tool. As such the resolution of machine tools made by different firms are not directly comparable.

13.1.2 Accuracy of Existing Commercial Meso-Milling Machines

There are two basic approaches to measuring the accuracy of a CNC machine tool. The first method, which is not supported by any international standard, is to measure the resulting workpiece for conformance to dimensional specifications. The second method, involves measuring the positional accuracy of the individual feed stages at various absolute points in their travel as commanded by a reference output signal from the controller. Variations on this method are supported by the following international standards:

- NMTBA and ASME B5.54-92 (United States)
- ISO 230-2 (Europe)
- BSI BS 4656 Part 16 (British)
- VDI/DGQ 3441 (German)
- JIS B 6336-1986 (Japanese)

All of these standards use predefined methods for measuring forward accuracy, reverse accuracy, bidirectional accuracy, and position deviation. The values recorded are usually an average of several measurements, however how these values are averaged can differ depending on the statistical method (mean, median, average of min and max values, 3 sigma deviation, 6 sigma deviation, etc.) As a result, while some standards can be directly compared for forward and reverse accuracy, notably the NMTBA and VDI standards, other measured values such as positional deviation can differ by over 40%.

Moreover the methods used for measuring the feed-stages position can differ from one standard to another: while most standards accept the use of glass-scale incremental encoders to measure position, only the ASME B5.54-92 standard specifies the use of a laser interferometer for measuring position. This standard is also the only one to specify operating conditions during measurement, as well as the setup conditions when commissioning the machine.

In general a meso-milling machine can have an accuracy ranging from 0.1µm to 10-30 µm. Not surprisingly, the machine’s accuracy correlates well with machine price. Because the machine builder can choose whichever standard he/she prefers for reporting accuracy values, generally the accuracy values reported in machine specifications are not directly comparable from one builder to another.

Other aspects of machine tool accuracy include spindle runout and accuracy tests for rotary axes. The standard which is the most comprehensive for all of the factors affecting machine accuracy is the ASME B5.54-92 standard which also includes contouring performance tests.

13.1.3 Repeatability of Existing Commercial Meso-Milling Machines

All of the previous international standards used to measure machine accuracy include methodologies for verifying machine repeatability.

Repeatability is a measure of a feed-stages precision and is a good indicator of the lost motion which occurs when a machine is reversed in direction. Lost motion is when motion is commanded, but there is no noticeable output until the machines final position is determined. Lost motion can be the results of deficiencies in mechanical transmission such as backlash in gears, timing belt stretch and flutter, etc. In general, the larger the stage’s travel, the greater the compensation required for lost motion. “Repeatability” tests in which a stage is zeroed, commanded to a forward position and then reversed an equal amount is a good measure of lost motion. In most standards, the gauge used for lost motion is the “Bidirectional Repeatability” measure. Unfortunately for the same machine, this measurement can differ greatly from standard to standard, depending on the statistical measures used.[14]

In general, repeatability values for commercial CNC meso-milling tools are on the same order of magnitude as accuracy values.

13.1.4 Overview of the Controller Vendor Market.

The controller market includes controllers which are proprietary to individual machine builders such as Fanuc controllers, and controllers from third party manufacturers such as Heidenhain, and Delta Tau. The latter are motion control expert who derive a significant portion of their business from the machine tool industry. Proprietary controllers such as Fanuc can be bought and used by small machine builders for a licensing fee, but they typically have a closed architecture and do not easily permit modification by the small machine builders. As a result the g-code files which these machine can accept as input is typically advertized as Fanuc g-code.

On the other end of the spectrum controllers such as Delta Tau controllers, are open architecture and can be tailored by the machine builder to, not only use different control algorithms, but also to read many different formats of g-code depending on what the individual machine builder wishes to market.

Fanuc controllers are typically used for very specialized machines, while many small and medium sized machine builders will frequent vendors such as Delta Tau.

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[14] Klabunde, S., Schmidt, R. How accurate is your machining center. Modern Machine Shop, Mar 1998, Vol. 70 pg.82

13.2 Discussion of the Hardware Used in a Meso-Mill Machine Tool and the Implications for Control.

13.2.1 Choice of Motors

There is a variety of methods used for actuating desktop meso-milling machines, which include Stepper motors, servo motors, linear motors, piezoelectric motors and piezoworm motors. Each has their advantages and disadvantages.

Many inexpensive meso-milling machines use stepper motors, while medium-priced commercial machines commonly use DC brushless motors attached to a leadscrew. High-end machines sometimes use linear motors, while piezoelectric actuation and piezoworm actuation are methods currently being researched and developed.

The advantages to stepper motor include the occurrence of less noise during dwell periods and hence more stable operation, while fewer sensors are required to control the machine. In addition modern microstepping drives which subdivide the motor steps, offer improved accuracy and repeatability. CNC controllers can also use simulated feedback with stepper motors: in this arrangement back emf from the stepper motor bridge is sensed by the microstepping drive and fed back to the CNC controller. Following error can thus be determined for a stepper motor.

The downside to stepper motors is that due to the limited instrumentation and feedback, sophisticated control algorithms are not possible. Moreover real-time monitoring of absolute position is not possible.

Rotary AC or DC brushless servo motors are used in combination with leadscrews to generate linear motion. The resolution of the resulting assembly can be as much as 0.1µm with an an unidirectional repeatability of 0.3 µm[15]. Servo motors offer the advantages of real-time monitoring of position, but require the use sensors with the same resolution as the leadscrew (0.1µm), when used in meso-milling applications. As a result the overall cost of instrumentation is significantly higher. The primary advantage of servo motors is that sophisticated control algorithms can be used, and some CNC controllers even allow the elimination of amplifier drives as the CNC controller can also perform the motor commutation.

The disadvantages to servo motors are the higher inertia and increased compliance when compared to a linear motor. Moreover because of this increased compliance of the leadscrew, rotary encoders need to be placed between the servo motor and the leadscrew, thus creating packaging constraints.

Linear motors offer some significant advantages, but are more costly, hence their use on high-end machines. They generally offer a resolution which is equivalent to precision rotary motor leadscrew stages (0.1µm), however they offer superior acceleration capabilities due to their lower inertia. Another advantage to linear motors is that the stiffness of the drive is no longer a function of the stiffness of the mechanical assembly, since there are only two mechanical components, but rather is a function of the controller. Therefore, the performance of the feed stage is more dependent on the controller algorithm and less on the mechanical components.

Piezoelectric drives are high resolution devices but have a very low travel range. As such they are commonly stacked on top of serial stages which are used for coarse positioning. The

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[15] PI M-238 datasheet, pg1,www.pi.ws

resolution of a piezoelectric stage is approximately 0.1 nm, and they have a travel range between approximately 50µm to 1.8 mm[16].

Piezoworm drives offer a high resolution, in the order of a few nanometers, and have fewer limitations on their travel range which is in the order of a few 100 mm. They can rely on simple-construction, high resolution linear encoders for feedback. These drives work by using a series of clamp and extension steps of the piezo material to move a slider. In one scenario, a dynamic slide mechanism consisting of two piezoelectric actuators serve to clamp on to a slider, while a third piezoelectric stack extends and moves the slider in a series of clamp release motions. These drives are currently sensitive to vibration and are an area of ongoing research. In addition, similar to stepper motors, the slider mechanism requires a standalone inner control loop to sequence the stepping operations.

13.2.2 Choice of Sensors

Sensors can range from simple gate switches used with stepper motors for homing and for imposing limits on travel, to encoders used in closed loop feedback in order to determine absolute position of the feedstage. A non exhaustive list of sensors which could be included on a meso mill CNC tool is:

- Proximity sensors for homing.
- Opposed beam laser gate switches for homing.
- Mechanical limit switches for preventing overtravel.

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[16] P620.2 PI Hera Piezo Stage datasheet, www.PI.ws

- Linear encoders (incremental or absolute) for measuring position.
- Rotary encoders (incremental or absolute) for measuring position.
- Laser interferometer for measuring position.
- Accelerometers on the spindle for measuring tool chatter.
- Encoders used on the spindle for vector control.

The choice of encoders depends on what type of information is required. For a stepper motor, encoders may not be needed, but an accurate and repeatable homing switch is required in order to provide a consistent reference point. After the reference point has been established, the microstepping drives can proceed to count and subdivide the motor steps. Instead of sensors providing feedback, the microstepping drive estimates the back emf and provides an estimated following error to the CNC controller. An opposed beam homing sensor, depending on the homing speed can provide a repeatability of 0.6µm, while proximity sensors (capacitance or inductance), used in the same capacity would provide a repeatability in the order of 10 to 100µm.

When servo motors are used, an accurate and repeatable switch such as an opposed beam or proximity switch is insufficient, as a measure of distance must be provided. The machine designer may use the absolute or incremental, rotary or linear encoders, however a laser interferometer is the most accurate method for measuring position, as these sensors have an accuracy and repeatability in the order of one half the infra-red wavelength (i.e or approximately 1 nm).

Other sensors such as accelerometers, used to measure tool vibration, can be used for sensing tool chatter. Ultrasonic sensors are also used at the macro scale for sensing the change in noise pitch due to tool wear.

Limit switches, as a safety device, are desirable on all feed stages in order to prevent runaway motion, and to prevent damage to the mechanical components.

13.2.3 Choice of Guideways

The choice of guideways used in meso-milling machines includes:

Box ways

Linear bearings

Air bearings

Box ways are sturdy means of providing directional control to feed stages. They are typically used with rotary motor-leadscrew assemblies. Box ways consist of a U shaped base with a slot along the side of the bases, and a saddle which rides along the base and to which are attached gibs, made from friction material, via set screws. While suitable for large CNC machines, they create a lot of friction in the drive and are thus less suitable for meso-milling where movements are smaller and friction hysteresis has a more predominant role.

To counter frictional effects, linear bearings can be made from ball bearing or roller slides mounted to a straight base. In addition journal bearings can be mounted on a cylindrical rod and thereby provide directional control. These slides can carry lower payload and thus are more suitable for meso-milling machines.

Air bearing are used on some high-end machines, because they are less prone to thermal deformation. They are however less stiff than other bearing types, and grooves are sometimes added to the raceways in order to create aerodynamic lift and thus improve stiffness.

13.3 Choice and Selection of a CNC Controller for Use in the Development of a New Meso-Milling Machine

As the above discussion indicates, the development of a new CNC meso-milling machine should incorporate a CNC controller which has an open architecture so that the inverse kinematics of a proprietary parallel mechanism can be included into the controller. Moreover an open architecture controller will also allow the implementation of control algorithms which are currently the subject of academic research.

The CNC controller should include a DSP processor which can handle the extensive numerical computations required to implement the motion programs. The controller is thus a standalone computer which can execute motion programs, and make decisions such as varying the number of interpolations steps based on real-time processing, without requiring the processing power of a host personal computer. DSP processors typically run on a lower Clock speed than modern personal computers (around 80MHz) but are more suited for large bandwidth numerical computations. The controller will also have a firmware memory in order to store all the setup parameters for the CNC machine when power is shut-off.

Finally, the CNC controller must have means for rapid communication with the host computer, as this personal computer will typically be used as a Human Machine Interface. A high speed Ethernet or USB port is desirable.

A variety of motion controllers were investigated in order to satisfy the above criteria. A Turbo PMAC Clipper controller was chosen as a controller which is suitable for future development work in controlling a new parallel kinematic mechanism.

Before designing and building a new machine, this controller was used in the retrofit of an existing 3-axis desktop CNC milling machine. In this way, the intricacies of programming and setting up the CNC controller could be learned, and these lessons could be then incorporated into the designing, developing and building a new parallel mechanism meso-milling CNC machine.

13.4 Implementation of the Selected CNC Controller in a Retrofitted 3-axis Machine.

13.4.1 Aspects of Electrical Design

13.4.1.1 Overview and Description of the Controller Components

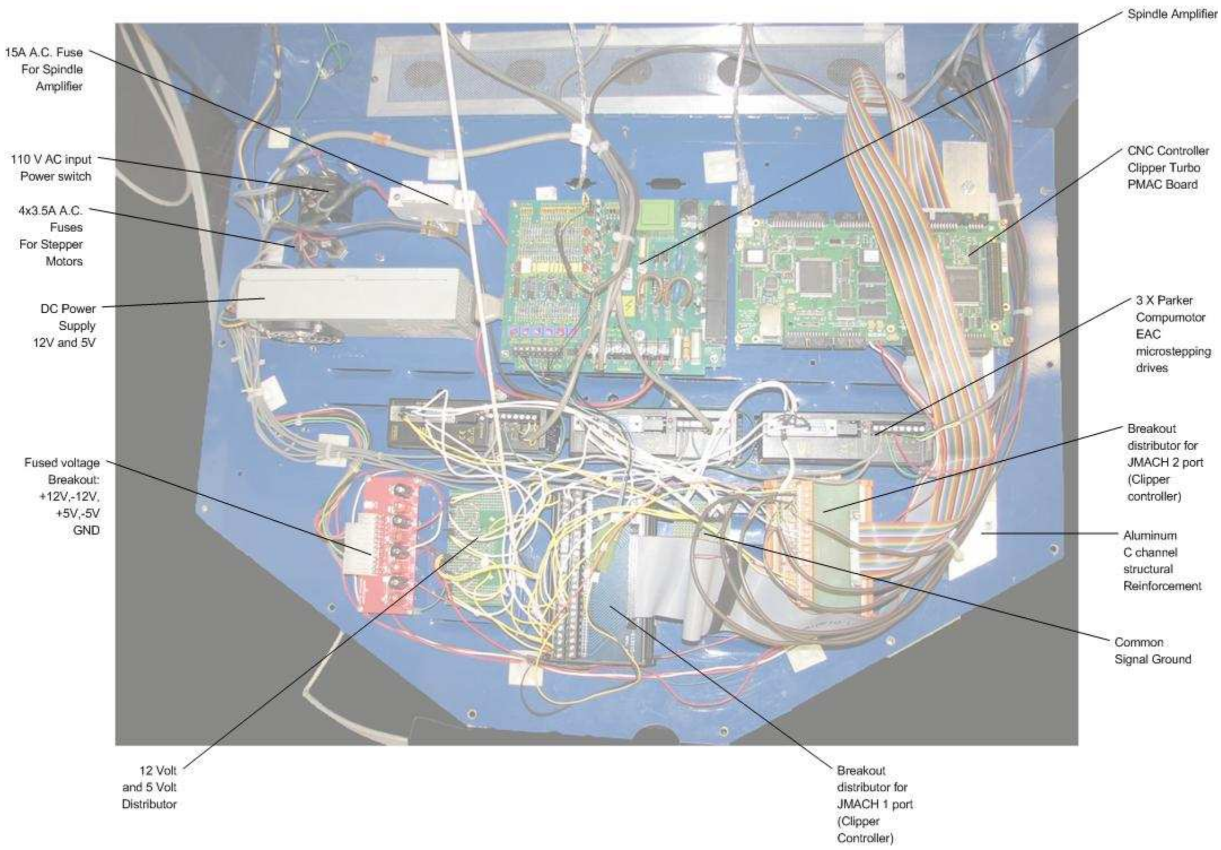


Fig.9 Controller layout in a retrofitted CNC machine

Starting with an input of input of 110 V A.C., power lines fused at 10A (Parker specification) are connected to the 3 Compumotor EAC-1 Microstepping drives. These amplifiers are fused internally at 5A but have capacitors requiring a power surge of 10A. The main 110V A.C power line is also connected to the spindle amplifier via a 15A fuse block. Lastly, this 110V A.C. line also powers a DC power supply via a 3.5A fuse. Not shown, as it will be connected following the submission of this report, is a emergency stop relay which will interrupt the 110V power lines going to the 4 motor amplifiers, when the emergency stop mushroom button is hit on the control panel in the front of the machine. This relay will not be connected to the power line supplying the DC power supply. The DC power supply is used to create signal voltage at both the 5V and 12V levels. This voltage is used to power the Turbo PMAC Clipper control board. The Turbo clipper PMAC board sends PULSE and Direction signal commands to the 3 microstepping Parker amplifiers. It also sends a DAC (Digital Analog Conversion) signal to the spindle amplifier. This Analog voltage which varies between 0 and 10V is used to regulate the speed of the spindle in an open-loop control manner. The breakout distributors attached to the JMACH1 and JMACH2 ports on the Turbo Clipper provide connections for the Pulse (Step + and –), Direction (+ and -), Fault (+ and -) and Shutdown (+ and -) signals as commanded by the CNC controller. In addition, JMACH 2 provides communication between the CNC controller and the sensors (HOME, Limit+ and -) which are used to control the feed stage motion. Other noteworthy components include and Optical isolator which is attached between the 0V level on the spindle amplifier and the signal ground. This isolator is required because the spindle amplifier does not use a GND level voltage: if the amplifier is forced to ground, then an overcurrent condition which will be created in the amplifier and a hardwired fuse on the circuit board will be blown.

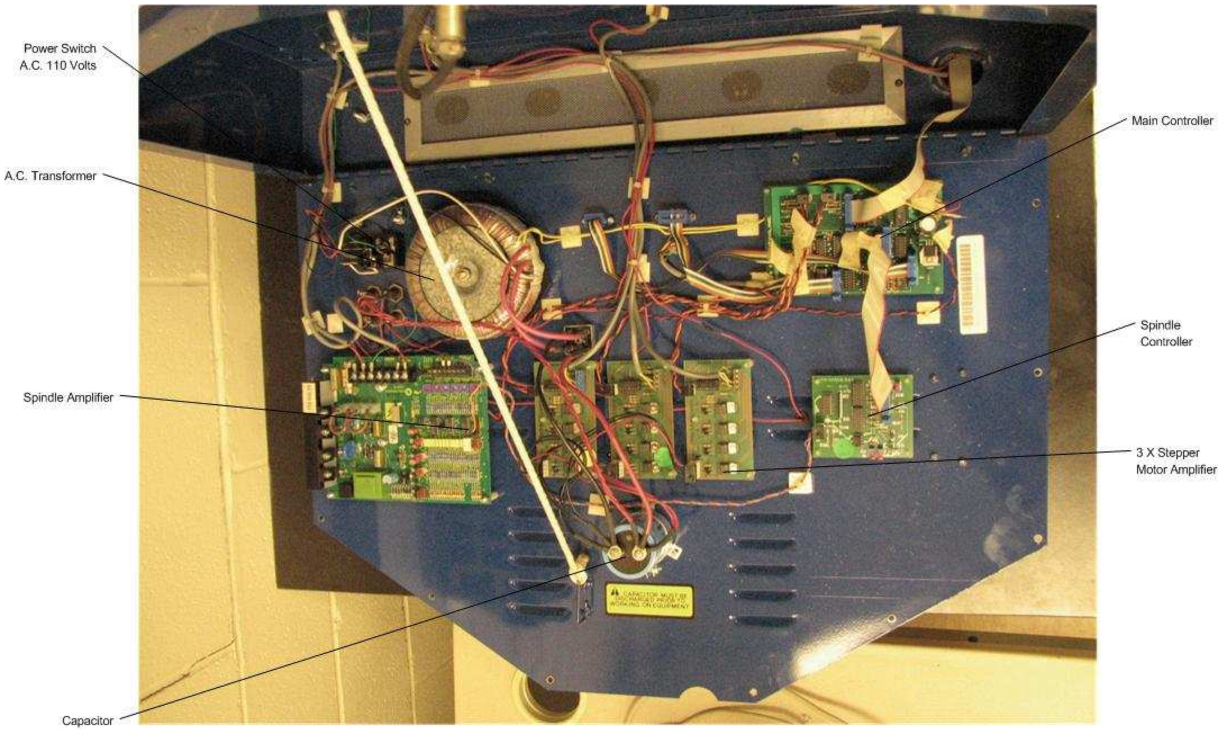


Fig.10 Controller layout before retrofit.

The figure above shows the controller which came with the CNC machine. The CNC machine design dates back to the late 1980s and used an IBM XT personal computer to regulate its functions. As evidenced by the two pictures, the electronic hardware has been substantially upgraded on the retrofitted machine, which added significant weight to the back panel of the machine. A C channel aluminum structural reinforcement was required to prevent the back panel from bowing, and the cooling capacity of the controller cavity had to be upgraded by adding two cooling fans to the cavity, one to draw in air and the other to expel it. In addition slots were created in the back panel, so that the fins on the back of the three microstepping drives could be suspended outside of the controller cavity and thus benefit from air circulation created by the natural convection of the outside ambient air.

Fig 11. Fins on the microstepping drive exposed to ambient air.

13.4.1.2 Discussion of the Controller Circuit and Schematics.

The connection of the different electronic circuit boards, required the use of many different types of integrated circuit interfaces. Some controller signals required two- transistor-logic (TTL), while others required the use of pull-up resistors in order to communicate between two circuit boards which operated at different voltage levels. The Direction and Pulse signals relied on TTL logic for communication between the CNC controller and the microstepping drives, while the Fault and Shutdown signals relied on pull-up resistors.

Please refer to Appendix (C) in order to view the wiring schematics which were implemented on this machine.

Yet another interface used was the optical isolator between the spindle amplifier and signal ground, because there was a voltage shift between the two lower bound voltage levels used on the CNC controller and the spindle amplifier.

13.4.1.3 Unipolar vs Bipolar Motor Wiring.

This 3-axis machine came with stepper motors which were rated at 200 count per revolution, and were wired according to a unipolar motor configuration. The microstepping drives required the motors to be wired according to a bipolar series configuration.

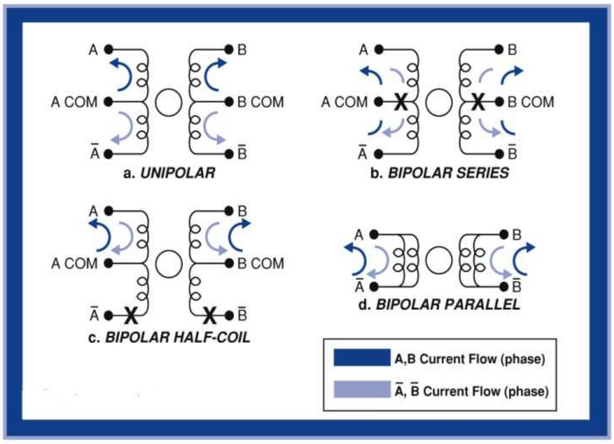


Figure 12. Bipolar vs Unipolar Stepper Motor Wiring.[17]

Therefore in order to make these motors suitable for bipolar operation, the joined A Common and B common lines were separated, and these live wires were capped. Failure to perform this operation resulted in a short-circuiting of the EAC-1 microstepping drives. In addition since the motors phases are now in bipolar series connection, the phase current supplied to the motors had to be reduced by a factor of 0.707 in order to provide the correct motor power and not overheat the motors

[17] NMB motor intro pg 82 NMB Technologies. www.nmbtc.com

13.4.1.4 Microstepping Drive Setup

Each microstepping drive had DIP switches which had to be correctly set in order to provide proper stepping operation. The DIP switches set the correct microstepping resolution, the desired phase current range, the step waveform, and whether anti-resonance control was provided by the microstepping drive.

The current settings for these DIP switches are as follows:

Resolution: 10,000 counts per rev.

Phase Current: 0.91 A.

Anti-resonance Control: Off

Waveform: Diminished by 4% 3rd harmonic.

Through experimentation, it was determined that these settings provide a stable and reliable feed-stage operation without triggering any motor faults.

13.4.1.5 Spindle Amplifier

The spindle amplifier was the only carry-over circuit board from the CNC machine`s initial controller setup.  As such, considerable troubleshooting was required in order to get this circuit board to work with the modern electronics. Please refer to Appendix(C) in order to view the manufacturer`s schematics of this board.

The resulting operation of the spindle motor, requires first the setting of the DAC voltage for the 4th motor via the CNC controller M-variable (M402), second, the disarming of the spindle interlock by pressing the silver pushbutton once one control panel at the front of the machine, and third throwing the toggle switch on the same control panel in order to turn on the machine.

Currently, there is no way in which the spindle can automatically be started through the CNC controller, however some logic for this purpose may be designed and wired in at a later date.

The voltage level for the DAC signal on the 4th motor is set on the controller by linearly interpolating between: M402 = 0 for 0V, and M402=1001 for 10V (Full spindle rpm).

13.4.1.6 Emergency Stop Circuit

The current standard for implementing an emergency stop in a CNC controller is to stop the operation of the motor commutation and to stop the commands issued from the CNC controller at the same time. It was decided that the most efficient method to implement to this shut off procedure is to interrupt the power supplied to the 4 motor amplifiers, while leaving the power supplied to the CNC controller intact. When the motor amplifiers shut down, a fault will be generated at the CNC controller which will prevent it from issuing further commands.

In order to perform the power interruption, a solid-state relay, a thyristor, rated at 50A, and requiring a signal voltage between 5V and 15V was purchased. This relay will be connected to a mushroom emergency stop button located on the control panel at the front of the machine.

13.4.2 Aspects of Mechanical Design (Structural Rigidity, Cooling and Ventilation, Belt Drives)

As previously discussed, because of the significant weight added to the back panel, a structural reinforcement C-channel was added in order to increase the moment area of inertia of the 3mm panel sheet, and thus prevent the panel from bending. This channel was placed underneath the Turbo PMAC controller and ensures that the area on the sheet panel where this circuit board is attached is very stiff. In this way, there is no risk that the controller circuit board is subject to bending and deflection.

As previously stated, allowances were made for the increased thermal energy generated by the microstepping drives and CNC controller, by adding two fans to increase air circulation inside the controller cavity in the back of the machine. Air is sucked-in on the lower right-hand side of the machine and expelled on upper left-hand side. In addition the cooling fins on the microstepping drives are suspended outside of the controller cavity in order to dissipate heat.

The stepper motors are connected to the leadscrews via a timing belt drive. Because the 2mm-pitch, 160-tooth, trapezoidal tooth belt used on the Z-axis feedstage was worn, stretched and frayed, this belt was replaced with a new belt. It was determine that the original length belt was very difficult to install, and required disconnecting the leadscrew sprocket as well as the motor sprocket. A new 165-tooth belt was ordered and some locked-center idler assemblies were created and added to each side of the belt drive. These locked-center idlers served to remove the slack in the larger belt, while facilitating installation since the leadscrew sprocket no longer has to be disconnected.

Fig. 13. Z-axis belt drive.

13.5 Controller Setup

13.5.1 Motor Setup

The CNC controller uses Pulse Frequency Modulation (PFM) to control the stepper motor speed and direction. In this manner, a square digital waveform of varying frequency is sent to the microstepping drive via the Pulse signal from the JMACH2 port on the Turbo PMAC Clipper controller.

The feed-stage motors are setup using the Turbo Setup program for stepper motors. Some of the noteworthy setup constraints involve:

Set commutation to be performed by the microstepping drive and not the controller

Using internal pulse train control as the encoder feedback,

Using a high voltage setting for positive fault flag, Enabling positive and negative overtravel limits.

Setting flag signals for the sensors to the same IC channel used by the motor,

I –Variables

I variables are the controller variables containing the resulting information which is pertinent to the motor and instrumentation setup. These variables are intended to be permanent, non-operable constants once the CNC machine is setup. They contain the addresses of the registers on the IC circuit which are responsible for the individual feed stage motor setups. They can be changed by accessing the control terminal in the PeWIN32 Pro2 software installed on the personal computer, or by running the Turbo Setup program. Moreover, when running Turbo Setup, a confirmation window is given, after each menu selection, which shows the setting of these I-variables. The I-variables can also be edited from this window..

Some noteworthy values for the I-variables used in this retrofitted 3-axis CNC machine include:

I7000 = 1001; Sets the PWM (Pulse Width Modulation) frequency to 29.4 kHz;

I7001=5; Phase clock 9.8 kHz

I7002=3; Servo Frequency set to 2.45 kHz

I7003=2258; Pulse width Frequency = 10Mhz

I7004=15, PFM pulse width = 1.528µsec.

(I7010, I7020, I7030) =8 for internal pulse direction feedback on stepper motors 1,2, and 3

(I7016,I7026,I7036)=3 for PFM output mode which is used for stepper motors, on IC channels 1,2 and 3

(I7017,I7027,I7037)=0; default polarity of the pulses for stepper motors 1,2 and 3.

(I7018,I7028, I7038) = 1; enable inversion of the stepper motor directions for motors 1,2 and 3.

I7046=0; for PWM output mode control for an analog signal on motor 4 (spindle motor)

I469 = 1001; DAC voltage limit of 10 V dc.

(I111,I211,I311)= 32000; for 2000 counts limit on motor following error;

(I116,I126,I136) = 16*number of motor counts to position the home offset in the middle of the stages travel range (typically 200,000 counts approximately);

(I197,I297,I397)= 1; set the trigger condition to an input trigger;

(I124,I224,I324) = $800,001; Activates overtravel flags;

(I7013,I7023,I7033)=0; In order to capture on the homing flag;

(I7012,I7022,I7032)= 3; In order to capture on Index high and Flag High triggers only;

(I223) = +32; sets homing speed and direction for motor 2;

(I123, I323) = -32 set homing speed and direction for motors, 1 and 3;

13.5.1.1 M-Variables

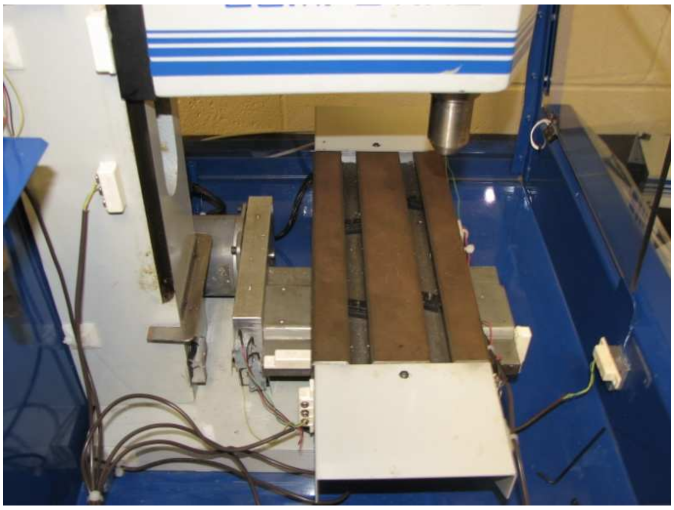
M-variable are used to contain the values that change during a motion program`s execution. These variables operate on the values contained in the registers which are pointed to by the I-variables. Default numbers are used to reference M-variables in this 3-axis machine setup.

One noteworthy M-variable is M402 which varies between 0 (0V for DAC4) and 1001 (10V for DAC4) and is used to regulate the speed of the spindle motor.

13.5.2 Sensor Setup

Since stepper motors are used on the feed stages, a limited amount of instrumentation is used on the feed stages. These include mechanical limit switches to prevent over-travel conditions, and homing switches which are used to provide a consistent and repeatable zero position.

13.5.2.1 Limit Switches



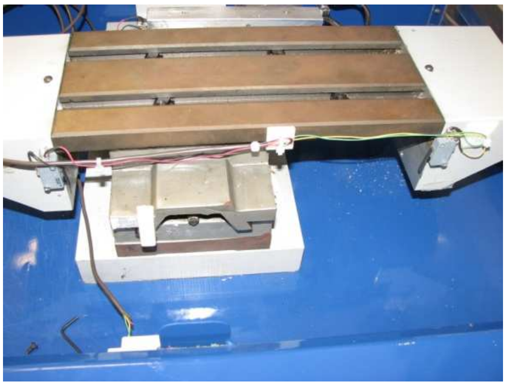


Fig.14,15&16: CounterClockwise from the top X-stage, Y-stage, and Z-stage limit switches re

For the Y-stage, as well as the X-stage, the mechanical switches are mounted on the moving platform of the stage, and motion is stopped when these switches make contact with the fixed base. For the Z-stage, a lever bracket was fabricated, and affixed to the moving platform holding the spindle motor. Two mechanical switches were mounted on either end of the stationary column, so that the desired travel range is reached.

13.5.3 Homing Switches

As an initial machine setup, simple capacitance door switches were used to provide gate which stop feed-stage motion after a homing command has been issued. These homing switches were all placed at the extremity of travel for each feed stage. In this way, when a homing command is issued, there is only one direction for the stage to proceed in order to reach the gate. If the gate was placed in the middle of the stage`s travel, than the homing switch could be approached from two directions. The CNC controller would not support this as the homing speed can only be specified in one direction.

In order to establish a zero or “home” position for each of the stages which is at the center of their travel, a home offset is specified in the software which will automatically move the feed stage a preset distance (in motor counts) away from the homing switch once this switch is reached when a homing command is issued.

13.6 Discussion and Development of a Coordinate System and Stage calibration procedure.

In order to execute g-code commands such as specifying a feed rate, a coordinate system must be established which establishes the feed stage displacement in linear units (mm) as opposed to rotary units (motor counts). Because the pitch on the leadscrews used in each of these feed stages is unknown, a procedure had to be developed in order to reliably establish the distance executed by the feed stage when motor counts are executed.

The procedure developed was as follows:

1. Motor jog Commands equal to 20,000 counts were issued for the X-stage
2. Using a micrometer with a resolution of 1 ten thousandth of an inch, and with outward facing probes, measurements were taken for the displacement of the moving stage from its base.
3. These measurements were repeated 10 times.
4. The feed stage was then issued a home command, and the sequence of ten measurements was repeated 3 times.
5. A rough approximation of the displacement per number of motor counts was established.

6. The command #2→3937X was issued. This command establishes coordinate system X to motor 2 and specifies that for 1 unit of displacement (i.e. 1 mm in this case) 3937 motor counts are required. In addition to Cartesian coordinate systems, other coordinate systems can be defined where the axes are not orthonormal, which would be useful for parallel kinematic mechanisms.

7. Not that the coordinate system is set-up, a command of a specific displacement was given to the X-stage

8. The actual displacement of the feed stage was measured and compared to the reference displacement.

   The two values were compared and since they differed, the 3937 constant was multiplied by the ration of the reference displacement divided by the actual displacement:

$$\frac{Reference\ displacement}{Actual\ displacement} * 3937 = New\ constant\ value$$

   Where $reference\ displacement\ = 2.54\ mm$

9. A new command was issued #2→(new constant value)X

10. Steps 8 and 9 were repeated iteratively until the reference displacement = actual displacement to 1 ten thousandth an inch on the micrometer.

The resulting axis definition was #2→3077.45X

The above axis definition was verified on the Y and Z-stages and found to accurate.

13.6.1 Resulting Resolution of the Feed Stages:

The resulting coordinate system definition is:

#1→3077.45Z; #2→3077.45X; #3→3077.45Y

This corresponds to feed stage resolution of 0.325µm per motor step. This resolution is higher than most commercial meso desktop CNC machines which use stepper motors and is a consequence of the incorporation of the specialized microstepping drives in the CNC machine. Please view Appendix (A) in order to view some advertized resolutions for commercial meso desktop CNC machines with stepper motors.

13.6.2 Repeatability Tests on the Homing Command.

Simple capacitance sensors are used as homing switches on this machine. In order to determine whether the zero position established was repeatable an experiment was conducted.

1. A Dial depth gauge with a magnetic base was borrowed from the machine shop. The dial gauge was a Teclock Dial gauge with a resolution of 1 thousandth of an inch.

2. The dial gauge`s base was located on the machining cavity floor, and the dial gauge was zeroed against a solid part of the moving platform of the X-stage. The zero position corresponded to when the feed stage was 50,000 counts away from the stage base.

3. A homing command was issued to the X-stage.

4. Once the machine came to a rest after the homing command, a command to jog the stage 50,000 counts in the negative direction was issued.

5. The dial gauge reading was then compared to the initial zero reading.

6. The above steps 3 and 4 were repeated several times.

The actual movement of the dial gauge was less than the resolution of this device and was estimated to be around 10µm. In order to improve on this measurement, ideally the same procedure would be performed with a laser interferometer instead of a dial gauge.

13.6.3 Selection of a Homing Sensor with Higher Repeatability for Future Use

The above procedure establishes a bi-directional repeatability which accounts for lost motion due to the backlash in the leadscrew and flutter of the rope-tow of the timing belt drive. However since the feed-stage has a resolution of 0.325µm, the sensors used do not take full advantage of the resolution provided.

Investigative searches were initiated for a homing gate switch with a higher repeatability. After reviewing many products, it was concluded that an opposed beam infra-red laser assembly consisting of a transmitter and a receiver offered the best solution. The advertized switch had a repeatability of 100 µseconds. If a homing speed of 32 steps per millisecond is used, then the repeatability of this homing switch is:

32Counts per millisecond * 0.325µm per count *100* 0.001 milliseconds/microsecond = 1µm.

If the homing speed is lowered to 20 counts/millisecond, then the corresponding repeatability is estimated at 0.6µm. A jog speed of 10 counts/millisecond, would achieve a repeatability of 0.3µm which is almost exactly equal to the resolution of the feed stage and is thus optimal.

13.7 Resulting Machine Specification

As the above experiments indicate the current machine configuration has some of the following specifications:

1. A resolution of 0.325µm
2. A bi-directional repeatability of 10µm
3. A jog speed of 20 Counts/ millisecond or 6.5 mm/second.
4. A max feed stage velocity of 50 counts/millisecond or 16.25 mm/second.
5. A maximum acceleration of 0.1 counts/square millisecond or 32.5mm/square second.

The reader may recall, that at the beginning of this thesis, the following machine specification targets were established:

1. A machine closed loop load stiffness of 100 N/µm.
2. A spindle runout of 0.8µm
3. A minimum spindle rpm of 50,000
4. A feed stage positional accuracy of 0.1µm.
5. A feed stage assembly resolution (actuator, encoder, and controller) of 10 nm
6. A feed stage feed rate of 2.54mm/s
7. A workspace of 300mmx300mmx300mm

Therefore, on this retrofitted machine, by changing the controller, a resolution of 325 nm is achieved and a maximum feed rate of 16.25mm/s is achieved. These results suggest that there is the potential to achieve the target machine specifications, when a parallel kinematic machine is used with this chosen controller. However, these results also indicate that instrumenting a new meso-milling machine in order to achieve a position accuracy of 0.1μm will pose some significant challenges. The current choice of sensing technology which can achieve this level of accuracy is very limited and the most probable candidate is the laser interferometer which is costly.

13.8 Implementing a g-code motion program

The sample motion programs 1000, 1001 were downloaded from the Delta Tau website, and stored into the controller`s firmware. Because the g-code file format, as created by many computer-aided manufacturing software can vary somewhat, Delta Tau enables the machine designer to customize the g-code commands as he or she desires by adjusting the above motion programs. The 1000 motion program essentially translates g-code commands into native commands recognized by the Turbo PMAC Clipper controller. The 1001 motion program contains the M-variables settings which dictate spindle speed and tool compensation radius.

Using a pen as a stylus located in the spindle, a pad of paper was affixed to the X feed stage, and some simple motion programs which recreate the author`s initials CH in g-code language were downloaded to the controller and executed. The feed stages correctly executed the motions required to create the author's initials.

Future work may involve tailoring the motion 1001 program for such g-code commands as changing the spindle speed, and allowing for tool diameter compensation. In addition there are more extensive g-code commands which can be implemented into the 1000 motion program.

14. Conclusion

Open architecture controllers allow greater design flexibility which creates opportunities for designing and developing innovative new desktop CNC meso-milling machine tools. These new machines will embody the design objectives of offering improved accuracy, resolution, and stiffness while providing the manufacturing flexibility necessary to optimize an object function which could include minimum cycle time, or minimized removal of machining stock.

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PI M-238 datasheet, pg1,www.pi.ws

P620.2 PI Hera Piezo Stage datasheet, www.PI.ws

Appendix (A) Commercial CNC meso-milling machines

Maker	**A**	**B**	**C**	**D**	**E**		**F**	**G**
Model	**1**	**1**	**1**	**1**	**1**	**2**	**1**	**1**
Max No of Axis	**5**	**3-5**	**5**	**5**	**3-4**	**3**	**4**	**3-4** **(5 eventually)**
Configuration	**Horizontal**	**Vertical**	**Vertical**	**Vertical**	**Vertical**	**Vertical**	**Vertical**	**Vertical**
Spindle Speed	**-50,000 rpm** **-20,000 -100,000 rpm**	**-500 – 30,000 rpm** **-500 – 50,000 rpm** **-30,000-90,000 rpm** **-60,000-160,000 rpm**	**-50,000 rpm** **-70,000 rpm**	**-30,000 rpm**	**-50,000 rpm** **-10,000 rpm** **-39,000 rpm** **-50,000 rpm**	**-5000 rpm**	**2000 rpm** **-50,000 rpm**	**-18,000 rpm** **-40,000 rpm**
Resolution	**x-y-z (.001µm)** **b-c (10e-6 °)**	**0.1 µm**	**.05µm**	**0.0155µm**	**0.5µm**	**3.175µm**	**2.5µm**	**0.7µm**
Repeatability	**?**	**1 µm**	**~0.2µm**	**3µm**	**2.54µm**	**6.35µm**	**5µm**	**5 µm**

Maker	A	B	C	D	E		F	G
Model	**1**	**1**	**1**	**1**	**1**	**2**	**1**	**1**
Accuracy	**< 0.100 µm** **(position)**	**±2.0 µm** **4^{th} axis <10”** **(position)**	**±1 µm** **(position)**	**5µm** **(position)**	**5 µm** **(position)**	**25µm** **(position)**	**1µm** **(runout)**	**10 µm** **(position)**
Feed Rate	**x-z 0.5 m/min** **y 0.05 m/min**	**10e-5 – 6 m/min**	**20 m/min**	**12.7 m/min**	**0.002 m/min** **To 5.08 m/min**	**0.002 - 2.54m/min**	**0.002 m/min**	**6 m/min**
Total Travel	**x- 280 mm** **z -150 mm** **B-C 360°**	**x-250mm** **y-220mm** **z-200mm** **rot 360°** **swivel-10°to 100°**	**x-200mm** **y-200 mm** **z-150mm**	**x-203 mm** **y-203 mm** **z- 305 mm**	**x- 304 mm** **y- 178 mm** **z- 241 mm**	**x -305 mm** **y- 152 mm** **z-229 mm**	**x -150 mm** **y- 100 mm** **z-171 mm**	**x-421 mm** **y-217 mm** **z-200mm**

Make	A	B	C	D	E -#1	E-#2	F	G
Drive **Stages**	**Linear motor** **AC servo** **Air bearing**	**Linear motor** **AC/Servo/ Digital** **Hydrostatic bearing**	**Linear motor**	**DC Brushless Servo** **Lead screw**	**DC Brushless Servo**	**Stepper Motor** **Ballscrew**	**DC Brushless Servo** **Lead Screw**	**DC Brushless Servo** **Lead Screw**
Type of **4th and 5th axis**	**Swivel is on the spindle head** **Rotation is on the Workpiece**	**Workpiece trunnion** **4th rotation** **5th swivel**	**Workpiece trunnion**	**Workpiece trunnion**	**Workpiece Trunnion** **Single pivot**	**Workpiece Trunnion** **Single Pivot**	**Workpiece Trunnion**	**Workpiece Trunnion**
Spindle **Power**	**Air Turbine** **Air Bearings**	**Air Turbine**	**Electric DC**	**Brushless DC**	**Air motor**	**Brushless DC**	**Brushless DC**	**Brushless DC**
Footprint	**?**	**2500x2200x2100 mm**	**1651x104x2057 mm**	**2159x1880x1549mm**	**1219x914x1219 mm**	**660x825x825** **mm**	**460x510mm**	**510x710 mm**
Price	**~$1,000,000.00**	**~$280,000.00** **To** **~$290,000.00**	**$250,251.00**	**$47,995.00**	**$42,000.00 to $61,500.00** **(spindle speed** **is cost driver)**	**~$39,000.00**	**$28,900.00**	**~$16,000.00** **+** **$8000.00 (50,000 rpm)**

NOTES:

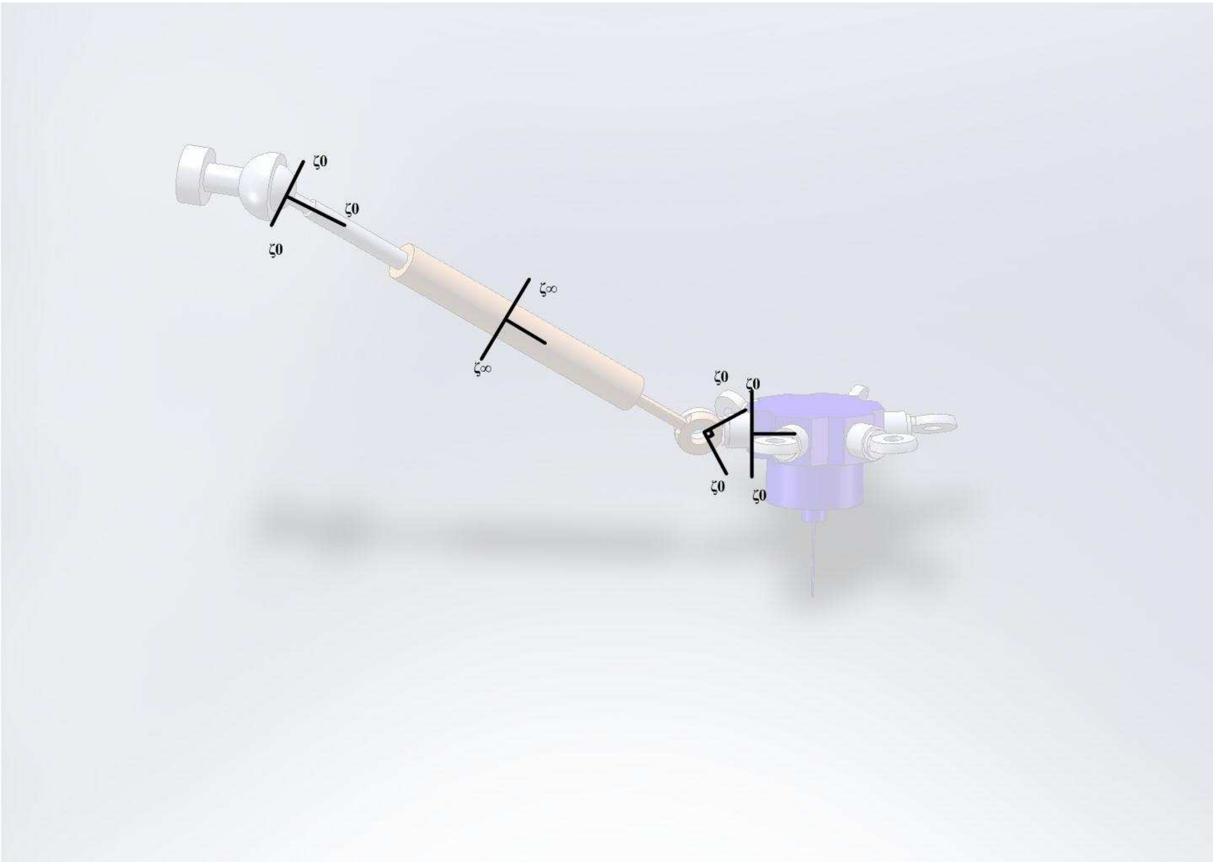
- All prices are in US currency.
- Machine Performance increases with price from right to left.
- Spindle speed is a large cost driver for these machines.
- Many manufacturers purchase their machine controllers from independent suppliers.

SUMMARY:

- A survey of micro milling machines indicates that the market is competitive with many machines having similar performance specs at the same price level.
- Except for the very high end Maker A, all machines reviewed had the 4th and 5th axes as part of the workpiece and not the spindle head.
- Two different strategies are used for reducing vibrations. The high end machines use a lot of mass to lower the resonant frequencies (witness the machine footprint), while most benchtop machines emphasize control of the force loop through the use of damping materials and reduced workspace height.

Appendix (B) Mobility Calculations for Concepts 1, 2 and 3

Concept 1 Mobility Calculation:



3-ζ0-2ζ∞ wrench system

- Calculate the mobility of one kinematic chain

$\mathcal{F}_j = d_j(n_j\text{-}g_j\text{-}1) + \sum f_i$ (1.1)

d_j= 5; n_j=4; g_j=4; $\sum f_i$ = 6

$\mathcal{F}_j = 1$

- Calculate the connectivity $\mathcal{C}$ of the moving platform in the single loop virtual chain:

$\mathcal{F}_j = f_j - \mathcal{C}$;

$\mathcal{C} = 5$

- Calculating the order of the wrench system c_j for the kinematic chain

$C_j = 6 - c_j$

$c_j = 1$ (1.3)

- Calculate the redundant Degree of Freedom (DOF) for each leg j

$R_j = \sum f_i - 6 + c_j$

$R_j = 1$ (1.4)

- Formulate the number of overconstraints in the Parallel Kinematic Mechanism

$\Delta = \sum c_j - c$ (1.5)

where c is the order of the wrench system of the Parallel Mechanism.

- Obtain the mobility of the mechanism $\mathcal{F}$ by solving:

$\sum c_j = 6 - \mathcal{F} + \Delta + \sum R_j$ (1.6)

$6 = 6 - \mathcal{F} + \Delta + 6;$

$\mathcal{F}$ - Δ= 6;

Therefore $\Delta = 0$ and $\mathcal{F} = 6$; Mobility of the mechanism is 6 and there are no overconstraints.

Concept 2 Mobility Calculation

- Calculate the mobility of one kinematic chain

$$\mathcal{F}_j = d_j(n_j\text{-}g_j\text{-}1) + \sum f_i \qquad (1.1)$$

d_j= 4; n_j=4; g_j=4; $\sum f_i$ = 6

$\mathcal{F}_j$= 2

- Calculate the connectivity $\mathcal{C}$ of the moving platform in the single loop virtual chain:

$\mathcal{F}_j$= f_j-$\mathcal{C}$;

3-ζ0-1ζ∞ wrench system

$\mathcal{C} = 4$

- Calculating the order of the wrench system c_j for the kinematic chain

$C_j = 6 - c_j$

$c_j = 2$ (1.3)

- Calculate the redundant Degree of Freedom (DOF) for each leg j

$R_j = \sum f_i - 6 + c_j$

$R_j = 2$ (1.4)

- Formulate the number of overconstraints in the Parallel Kinematic Mechanism

$\Delta = \sum c_j - c$ (1.5)

where c is the order of the wrench system of the Parallel Mechanism.

- Obtain the mobility of the mechanism $\mathcal{F}$ by solving:

$\sum c_j = 6 - \mathcal{F} + \Delta + \sum R_j$ (1.6)

$12 = 6 - \mathcal{F} + \Delta + 12$; $\mathcal{F} - \Delta = 6$; Therefore $\Delta = 0$ and $\mathcal{F} = 6$; Mobility of the mechanism is 6 and there are no overconstraints.

Concept 3 Mobility Calculation

- Calculate the mobility of one kinematic chain

3-ζ0-1ζ∞ wrench system

$\mathcal{F}_j = d_j(n_j\text{-}g_j\text{-}1) + \sum f_i$

(1.1)

d_j= 4; n_j=4; g_j=4; $\sum f_i$ = 6

$\mathcal{F}_j$= 2

- Calculate the connectivity $\mathcal{C}$ of the moving platform in the single loop virtual chain:

$\mathcal{F}_j$= f_j-$\mathcal{C}$;

$\mathcal{C}$ = 4

- Calculating the order of the wrench system c_j for the kinematic chain

$\mathcal{C}_j$ =6-c_j

c_j = 2 (1.3)

- Calculate the redundant Degree of Freedom (DOF) for each leg j

R_j=$\sum f_i$ - 6 +c_j

R_j = 2 (1.4)

- Formulate the number of overconstraints in the Parallel Kinematic Mechanism

$\Delta = \sum c_j - c$ (1.5)

where c is the order of the wrench system of the Parallel Mechanism.

- Obtain the mobility of the mechanism $\mathcal{F}$ by solving:

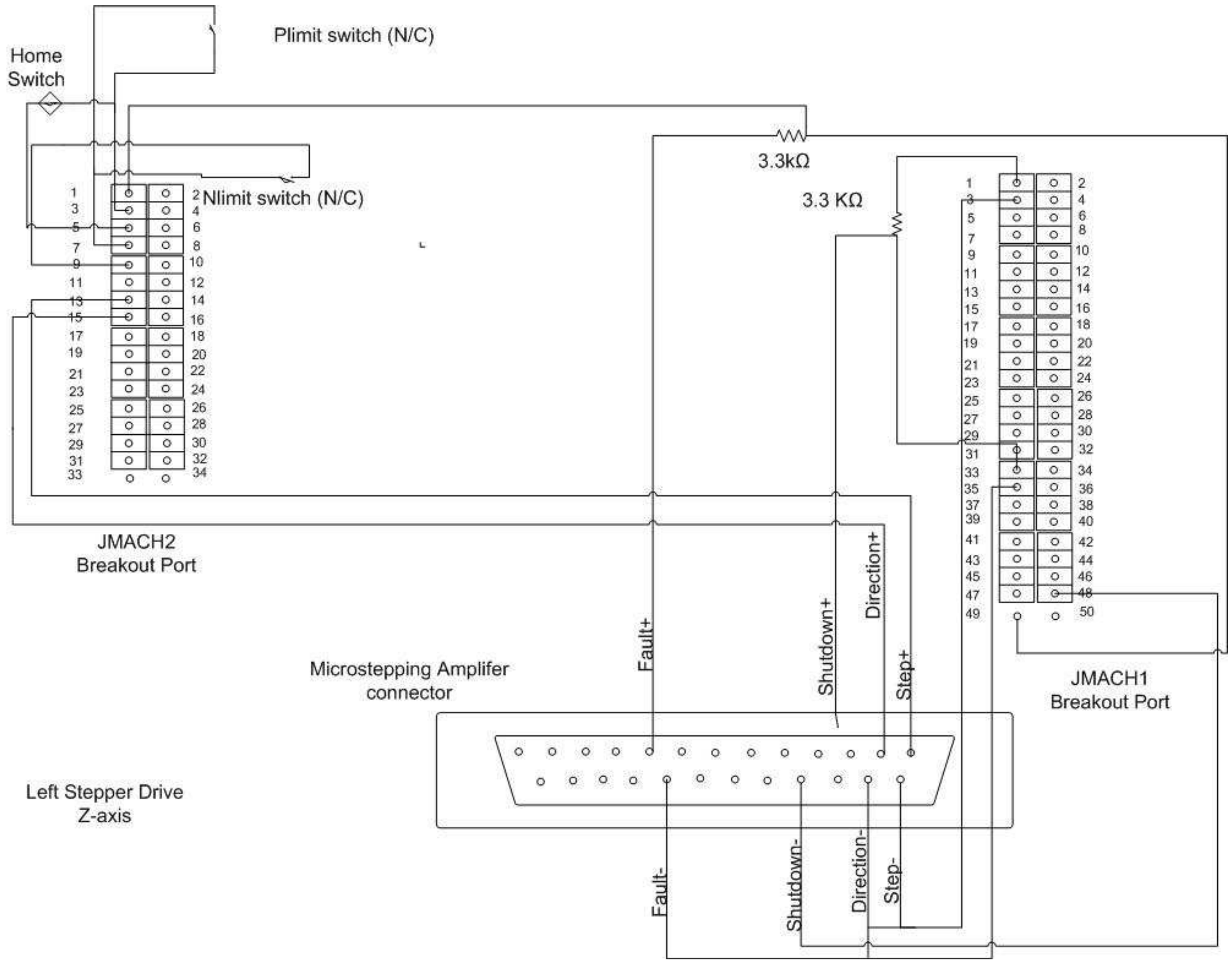
$\sum c_j = 6 - \mathcal{F} + \Delta + \sum R_j$ (1.6)

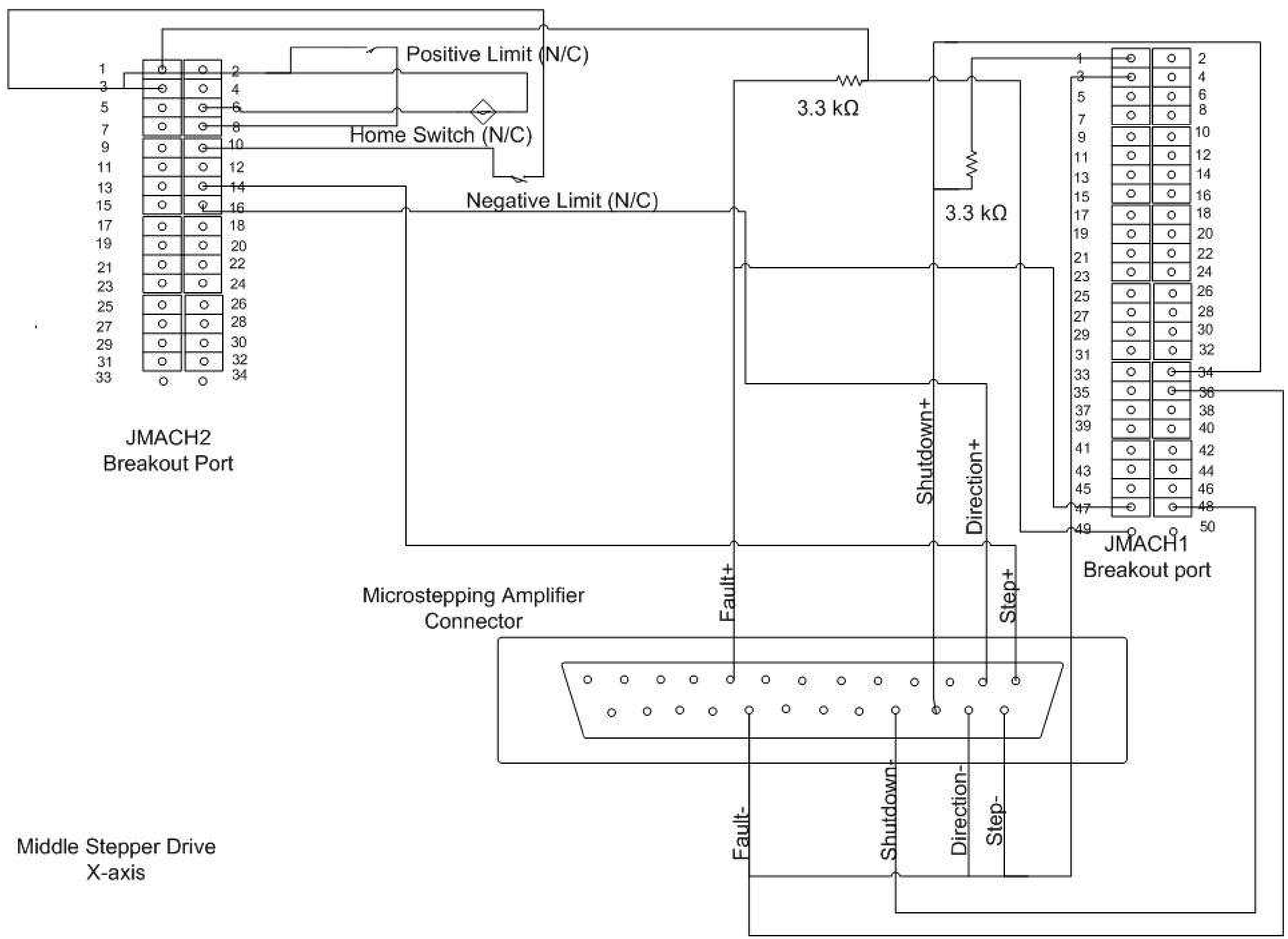
$6 = 6 - \mathcal{F} + \Delta + 6$

$\mathcal{F} - \Delta = 6;$

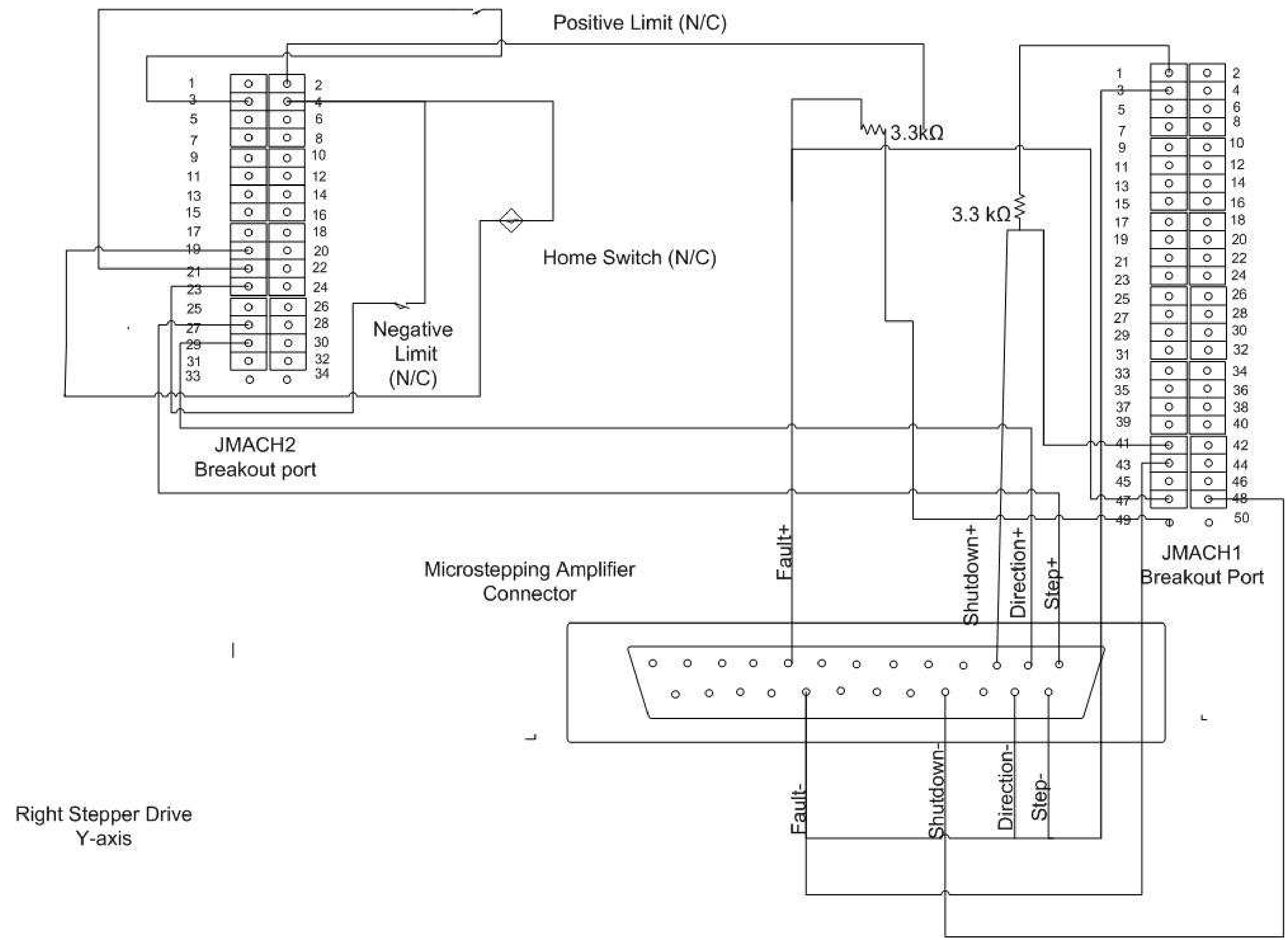
Therefore $\Delta = 0$ and $\mathcal{F} = 6$; Mobility of the mechanism is 6 and there are no overconstraints.

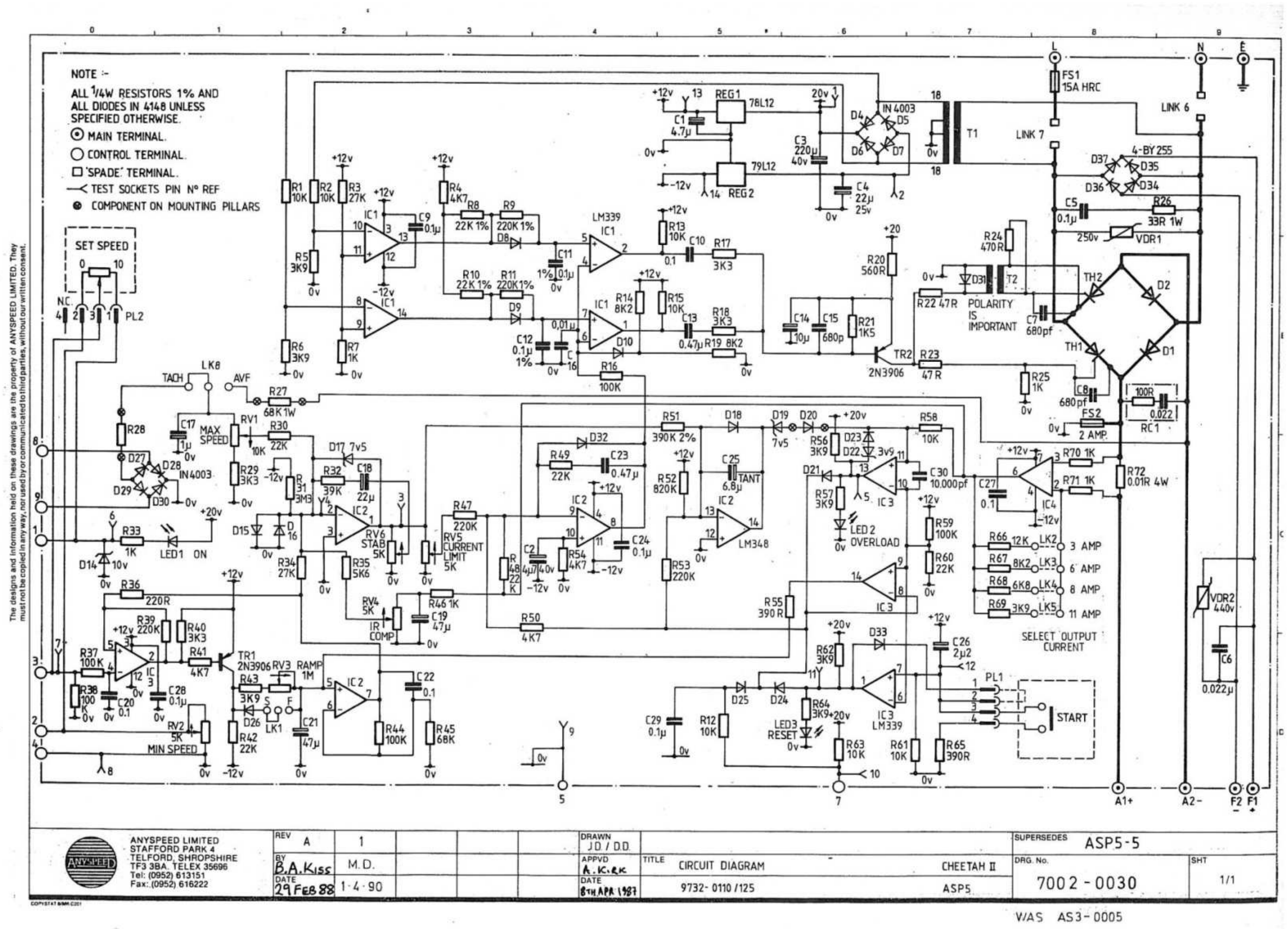
Appendix (C) Controller Schematics for a Retrofitted CNC Machine


Plimit switch (N/C)
Home
Switch
Nlimit switch (N/C)
JMACH2
Breakout Port
3.3kΩ
3.3 KΩ
JMACH1
Breakout Port
Fault+
Shutdown+
Direction+
Step+
Microstepping Amplifer
connector
Fault-
Shutdown-
Direction-
Step-
Left Stepper Drive
Z-axis



Positive Limit (N/C)
Home Switch (N/C)
Negative Limit (N/C)
3.3 kΩ
3.3 kΩ
JMACH2
Breakout Port
JMACH1
Breakout port
Shutdown+
Direction+
Fault+
Step+
Microstepping Amplifier
Connector
Fault-
Shutdown-
Direction-
Step-
Middle Stepper Drive
X-axis


Positive Limit (N/C)
Home Switch (N/C)
Negative Limit (N/C)
JMACH2 Breakout port
3.3kΩ
3.3 kΩ
JMACH1 Breakout Port
Fault+
Shutdown+
Direction+
Step+
Microstepping Amplifier Connector
Fault-
Shutdown-
Direction-
Step-
Right Stepper Drive Y-axis



Spindle Motor Amplifier

Appendix (D) 3-Axis User Manual

1. Initial Installation/Startup on a new Personal Computer

- Turn on the power switch on the back of the machine
- Plug USB adapter into computer
- If the CNC controller device driver does not load automatically, then go to the Windows control panel and add a new device driver. (As of present, the device driver for the Turbo PMAC2 Clipper controller does not function well with a 64-bit operating system, so the user should ensure that the PC has a Windows 32-bit operating system.)

   a. Check on add device, and let the operating system search for new hardware

   b. If no new device is found, then insert the Executive Suite CD#2 into the computer, go to browse and upload the driver file: PMACUSB.sys.

   c. In order for the driver to be successfully loaded, the following files should be loaded in their respective Windows directory:

      i. Windows\INF\PMACUSB.inf

      ii. Windows\System32\Drivers\PMACUSB.sys.

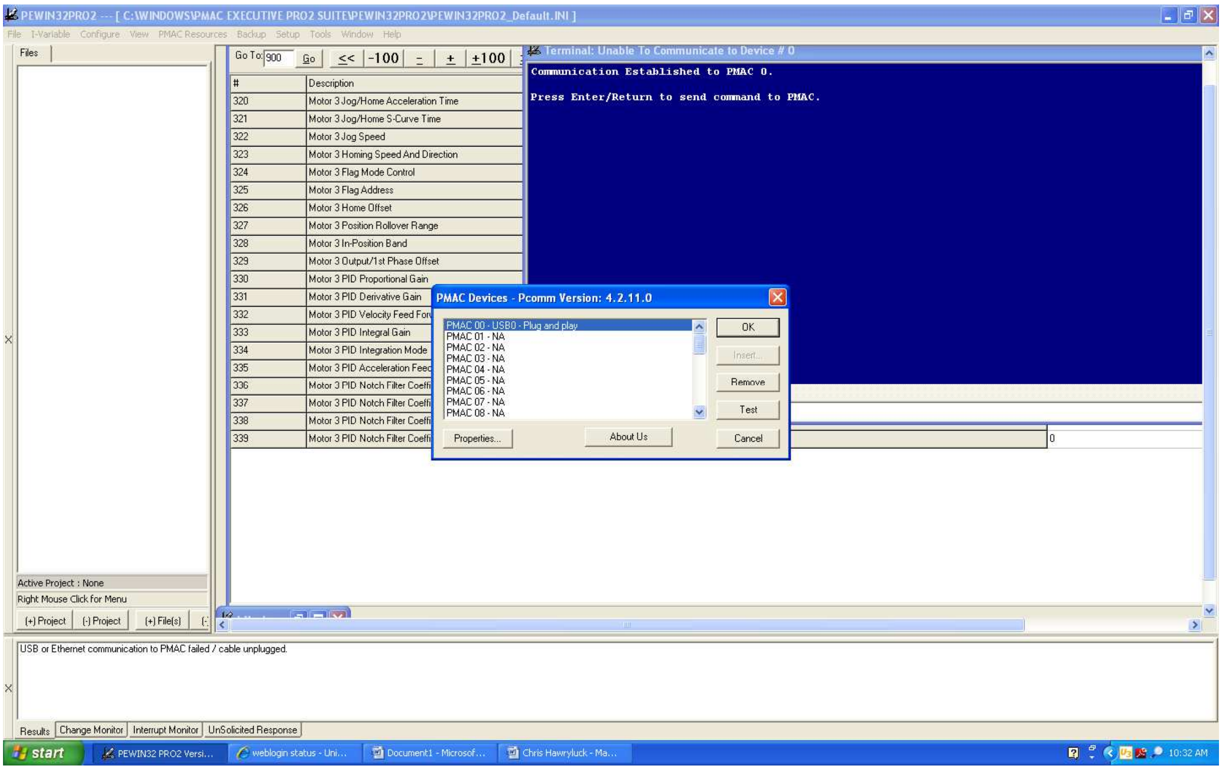
   d. The following driver should now be shown in the device manager:

   PMAC00-USB0-Plug&Play

- Install the Executive Suite CD#1 on the computer.

- Open the software PEWIN 32 Pro2

- The software will ask you to select a PMAC device in order to establish communication with the controller. Select the

- 

2. Startup Procedure

- Boot-up the Personal Computer

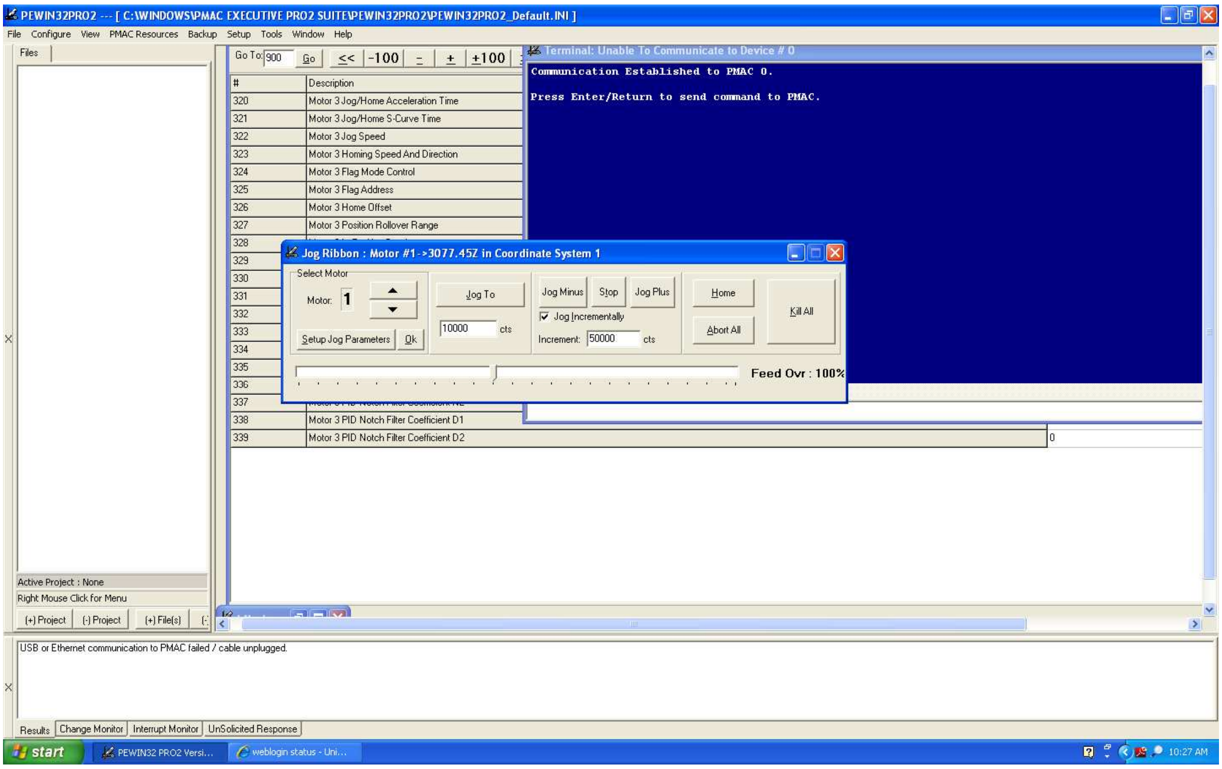
- Make sure USB cable from the CNC machine is plugged into the Personal Computer

- Turn-on the CNC machine

- Click on the PeWIN32 Pro2 icon on the PC desktop
- The software will automatically establish communication with the Controller on start-up
- If power to the CNC machine is cut while the PeWin32 Pro2 software isstill running, then communication must be re-established with the controller: go to the Configure menu in PeWin32 Pro2 and click on the Select PMAC submenu.
- Choose the “PMAC00 –USB0-Plug&Play” option

3. Jogging a feed stage

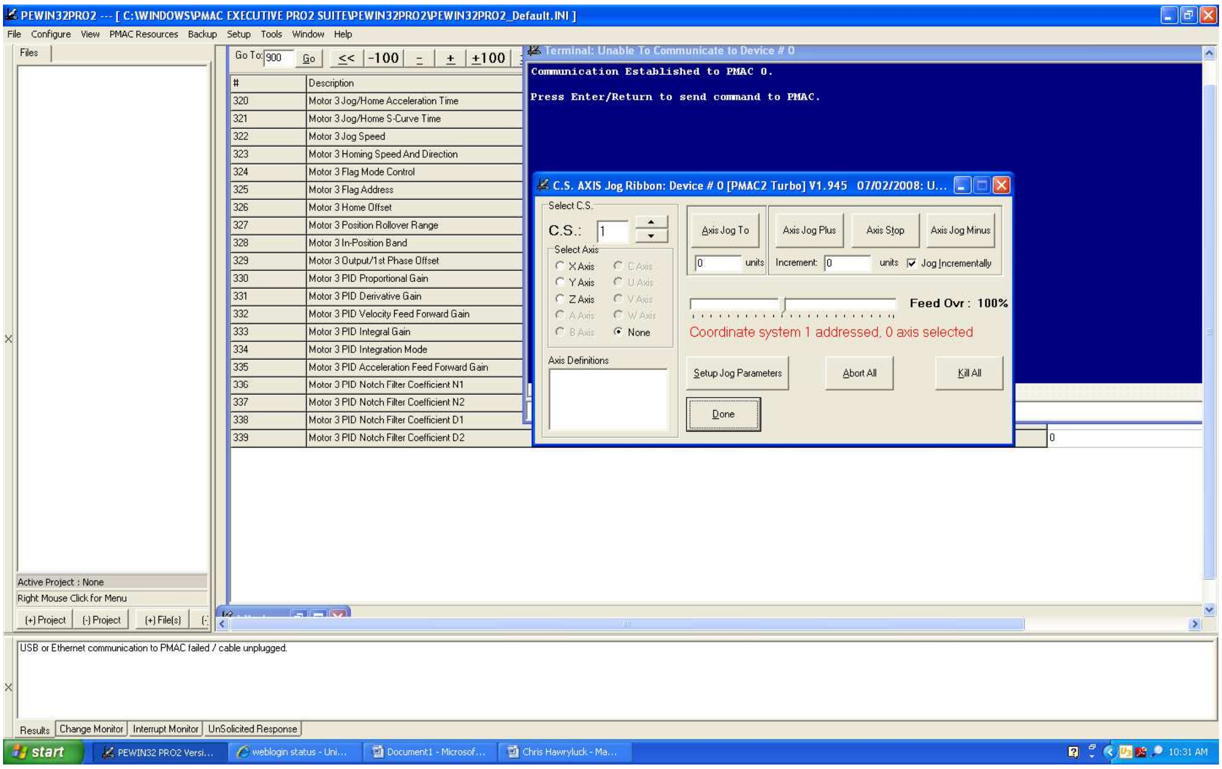
- Open the software PEWIN 32 Pro2 by clicking on the desktop icon
- Select PMAC00-USB0-Plug&Play
- The software establishes communication with the controller
- Go to the “View” menu
- Select the “Jog Ribbon” submenu



- Select the feed stage axis to Jog. The X, Y, and Z axis coordinates are indicated on a diagram which is on the panel facing the front of the machine. The positive and negative directions for each of these axes are also indicated on the front of the machine. Motor 1, 2, and 3 in the Jog ribbon correspond to feed stages Z, X, and Y respectively.

- Check the incremental motor count and input the number of forward or reverse motor counts. One motor revolution equals 10,000 counts. One motor revolution equals 3.25mm of feed stage linear displacement.

- If the operator wishes to move the feed stage in commands which have linear units [mm], then open the “CS Axis Jog Ribbon” submenu in the “View” menu



- Select the axis (X, Y or Z) and specify a linear displacement value [mm] in the incremental box, while checking the incremental jog for incremental displacement mode. Or enter an absolute displacement value in the absolute box.

4. Issuing a Home command

1. A “Homing” command can be issued in the “Jog Ribbon” previously referenced, when a particular X,Y or Z axis is referenced. Motor 1, 2, and 3 in the Jog ribbon correspond to feed stages Z, X, and Y respectively.

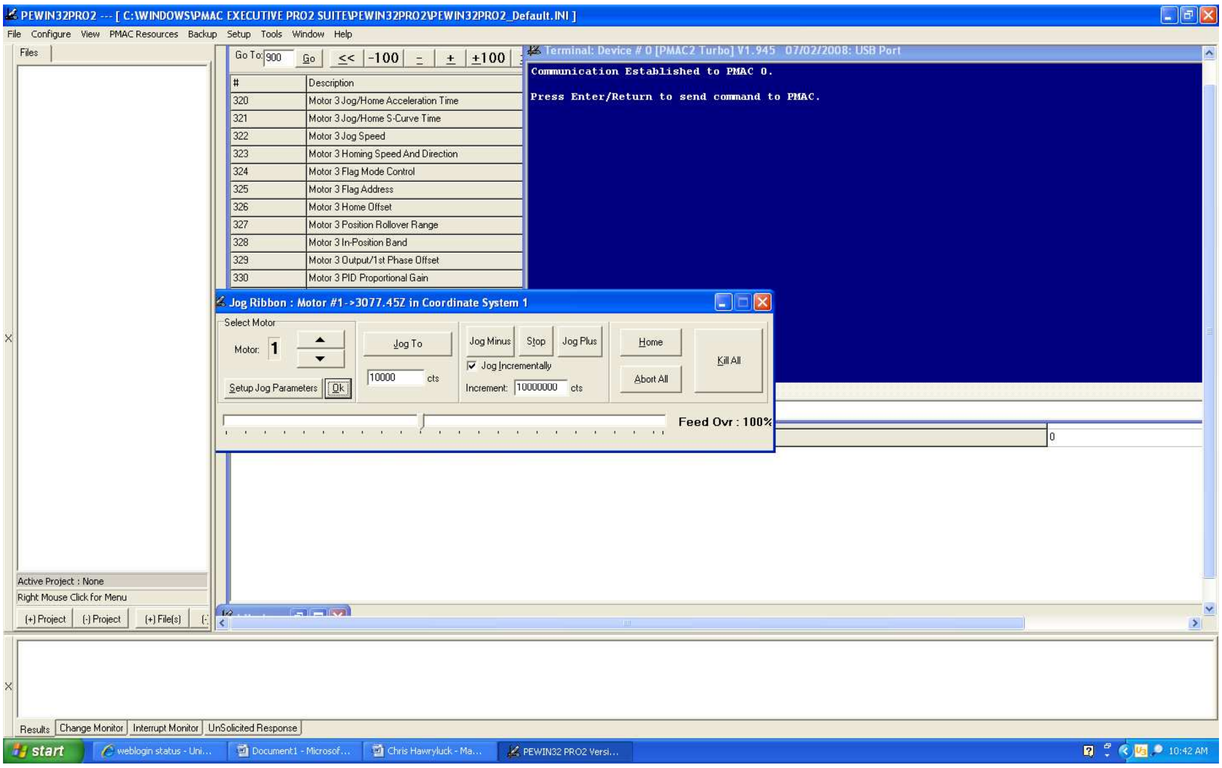
2. Alternately open the “Terminal” window in the PeWIN32 PRO 2 software. This window operates directly on the controller board.

3. Type “Home 1,2,3” and hit enter in order to home all 3stages at the same time.

5. To Kill a Motor

- Inside "Terminal" window of PeWin32 Pro2, type K

- Or go to the Jog Ribbon (in View menu), select the motor and hit the kill button



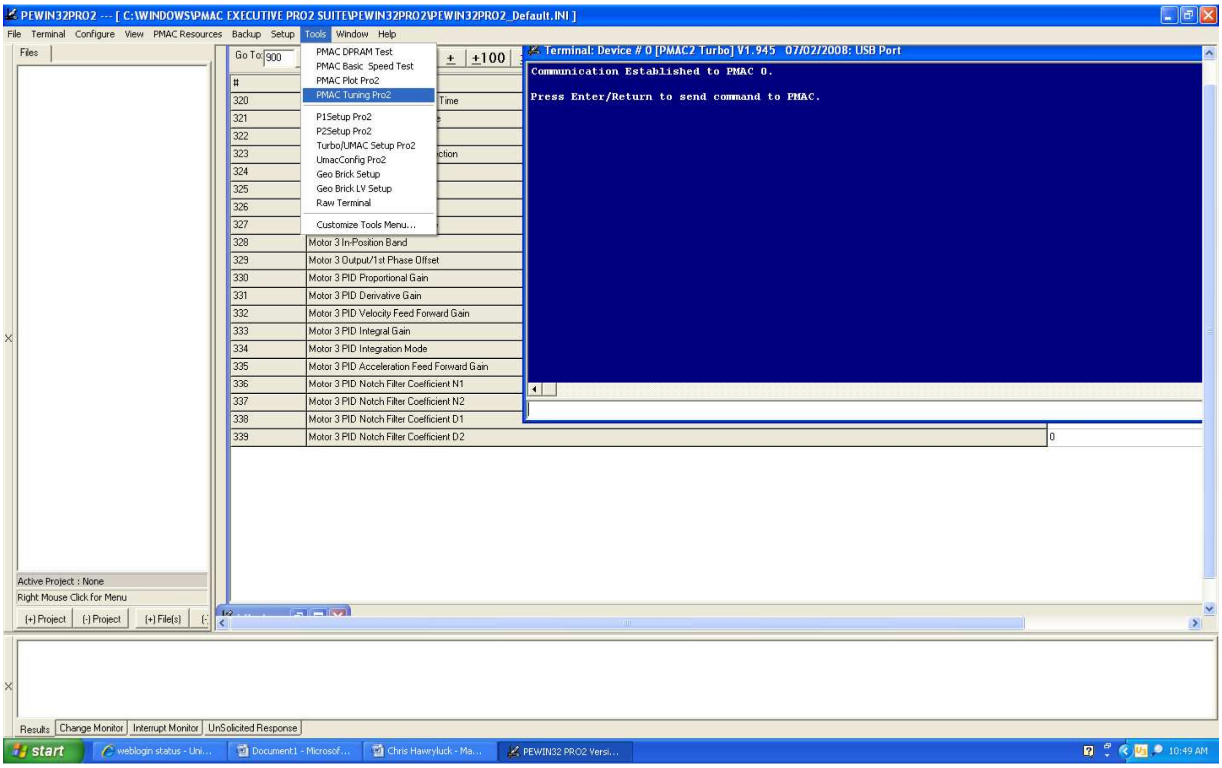
  - This acts immediately on the currently addressed motor.

  - The command is rejected if the motor is in a coordinate system that is currently running a motion program.)

6. To Enable a Motor

This feature is useful when you are trying to run a motion program, and you get the following error in the “Terminal” window: “One motor or more is in open loop”.

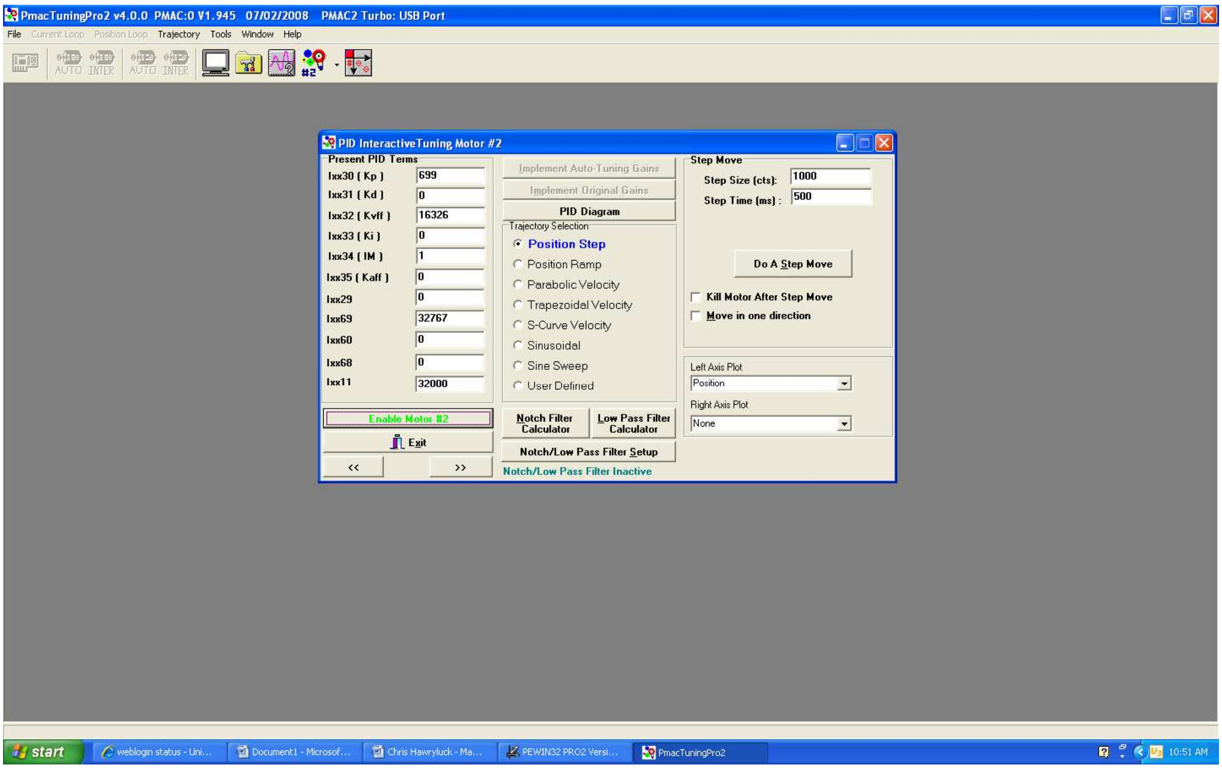
- Go to the tools menu, Go to the Tuning Pro software subroutine

- 

- Select the motor number of the stage that you wish to activate (Motor 1 is the Z-stage, Motor 2 is the X-stage, Motor 3 is the Y-stage)

- Click on the interactive icon

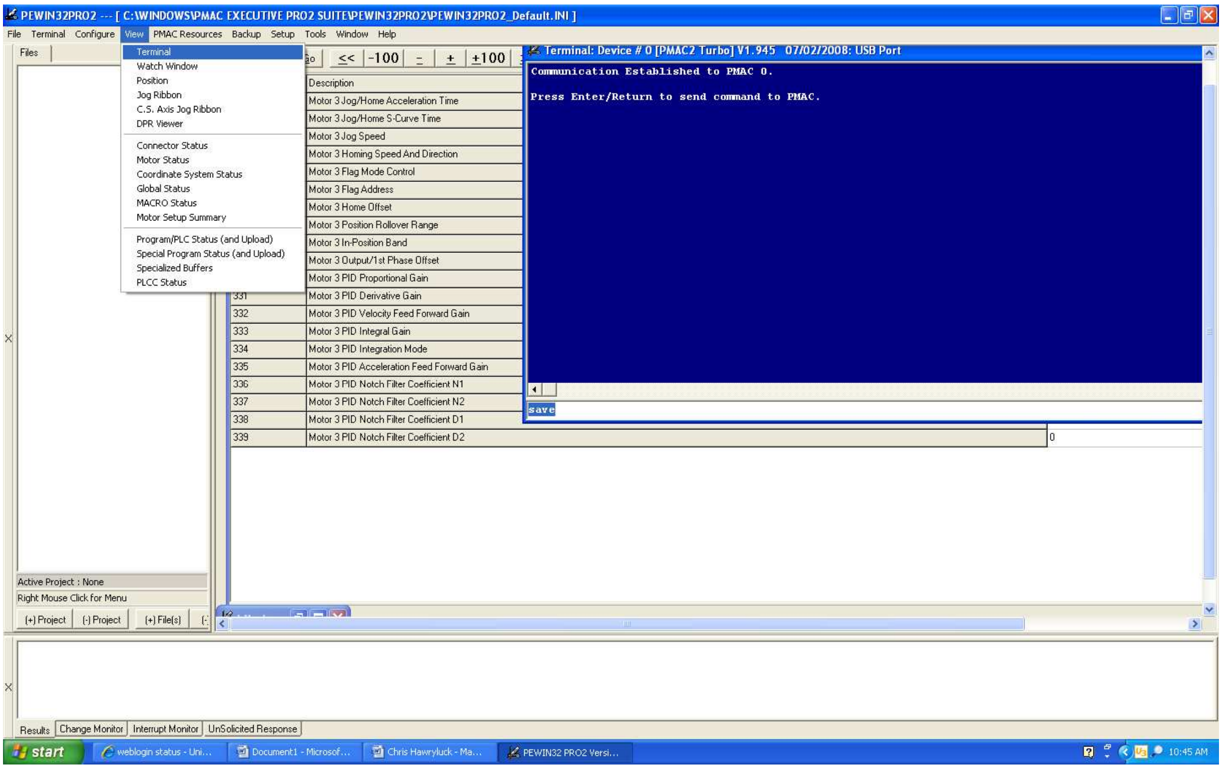
- Click on the enable motor button


PmacTuningPro2 v4.0.0 PMAC:0 V1.945 07/02/2008 PMAC2 Turbo: USB Port
File Current Loop Position Loop Trajectory Tools Window Help
PID InteractiveTuning Motor #2
Present PID Terms
Ixx30 (Kp) 699
Ixx31 (Kd) 0
Ixx32 (Kvff) 16326
Ixx33 (Ki) 0
Ixx34 (IM) 1
Ixx35 (Kaff) 0
Ixx29 0
Ixx69 32767
Ixx60 0
Ixx68 0
Ixx11 32000
Enable Motor #2
Exit
Implement Auto-Tuning Gains
Implement Original Gains
PID Diagram
Trajectory Selection
Position Step
Position Ramp
Parabolic Velocity
Trapezoidal Velocity
S-Curve Velocity
Sinusoidal
Sine Sweep
User Defined
Notch Filter Calculator
Low Pass Filter Calculator
Notch/Low Pass Filter Setup
Notch/Low Pass Filter Inactive
Step Move
Step Size (cts): 1000
Step Time (ms) : 500
Do A Step Move
Kill Motor After Step Move
Move in one direction
Left Axis Plot
Position
Right Axis Plot
None
start
10:51 AM

7. To Save a CNC motor configuration, I-variables, or to save motion programs to firmware:

- Inside PeWin32 Pro2, open the “Terminal” window

- Type “save”. The new machine settings are saved to firmware inside the CNC controller.

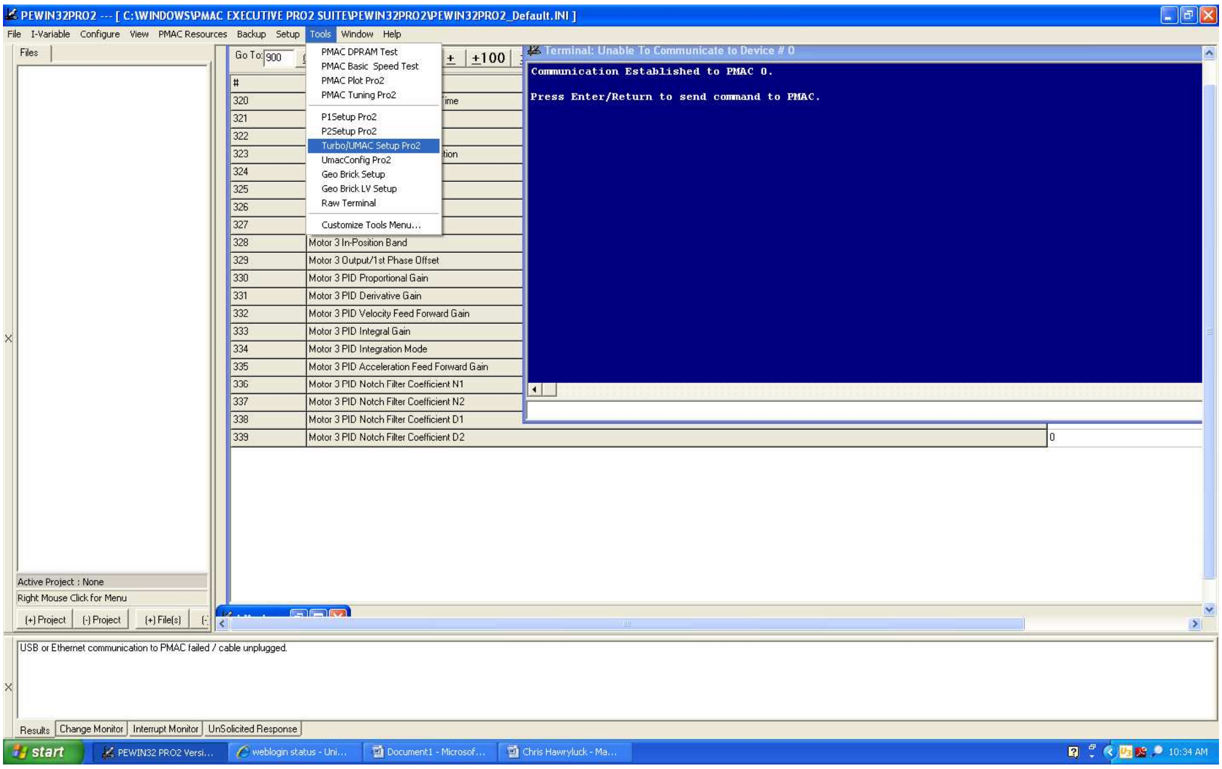


8. To setup a Motor

- Open PeWin32 Pro2 software and establish communication with the controller

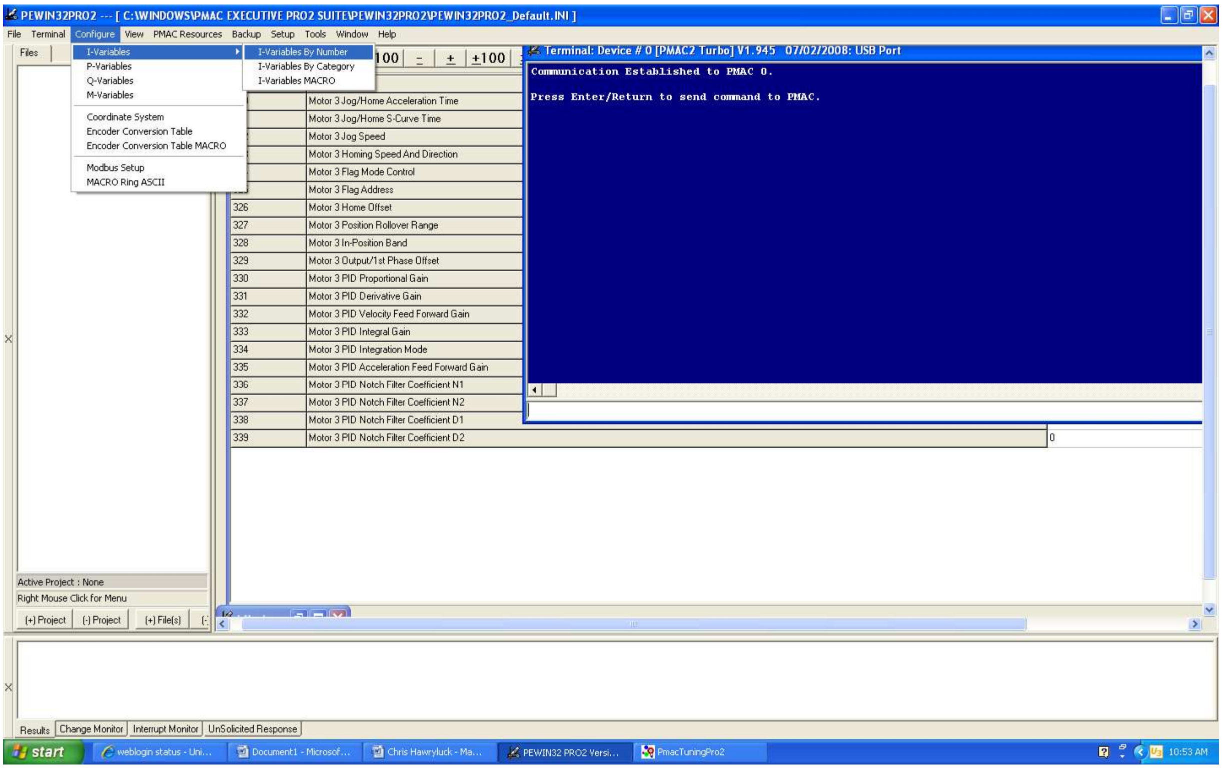
- Go to the “TOOLS” menu in the main menu

- Select the “Turbo Setup” menu and follow the interactive steps to add a motor.



- The new I-variable settings are displayed in Turbo Setup after each interactive window

- The resulting I-variable configurations can also be viewed by going to the “configuration” menu in the main menu and selecting I variables.



- For reference, the existing I variable settings for the stepper motors and spindle motors are as follows

I7000 = 1001; Sets the PWM (Pulse Width Modulation) frequency to 29.4 kHz;

I7001=5; Phase clock 9.8 kHz

I7002=3; Servo Frequency set to 2.45 kHz

I7003=2258; Pulse width Frequency = 10Mhz

I7004=15, PFM pulse width = 1.528µsec.

(I7010, I7020, I7030) =8 for internal pulse direction feedback on stepper motors 1,2, and 3

(I7016,I7026,I7036)=3 for PFM output mode which is used for stepper motors, on IC channels 1,2 and 3

(I7017,I7027,I7037)=0; default polarity of the pulses for stepper motors 1,2 and 3.

(I7018,I7028, I7038) = 1; enable inversion of the stepper motor directions for motors 1,2 and 3.

I7046=0; for PWM output mode control for an analog signal on motor 4 (spindle motor)

I469 = 1001; DAC voltage limit of 10 V dc.

(I111,I211,I311)= 32000; for 2000 counts limit on motor following error;

(I116,I126,I136) = 16*number of motor counts to position the home offset in the middle of the stages travel range (typically 200,000 counts approximately);

(I197,I297,I397)= 1; set the trigger condition to an input trigger;

(I124,I224,I324) = $800,001; Activates overtravel flags;

(I7013,I7023,I7033)=0; In order to capture on the homing flag;

(I7012,I7022,I7032)= 3; In order to capture on Index high and Flag High triggers only;

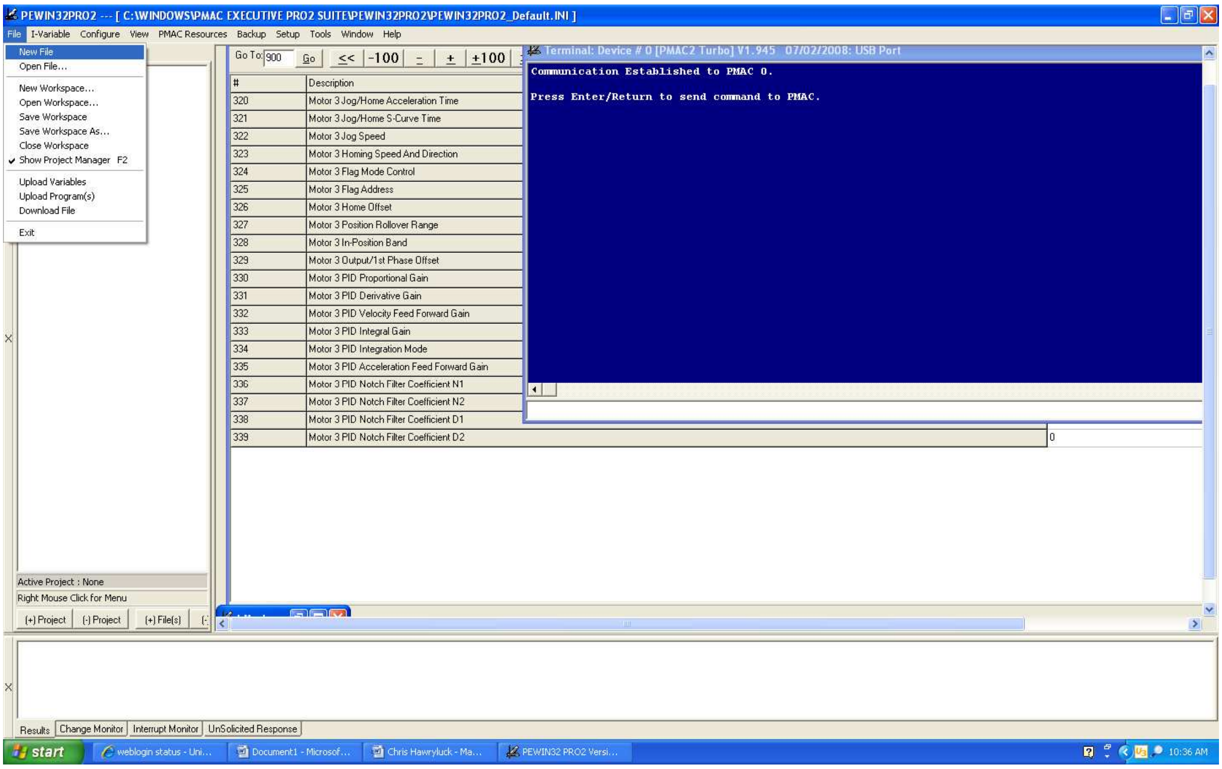
(I223) = +32; sets homing speed and direction for motor 2;

(I123, I323) = -32 set homing speed and direction for motors, 1 and 3;

9. To Edit a Motion Program

- Open PeWin32 Pro2 and establish communication with the controller

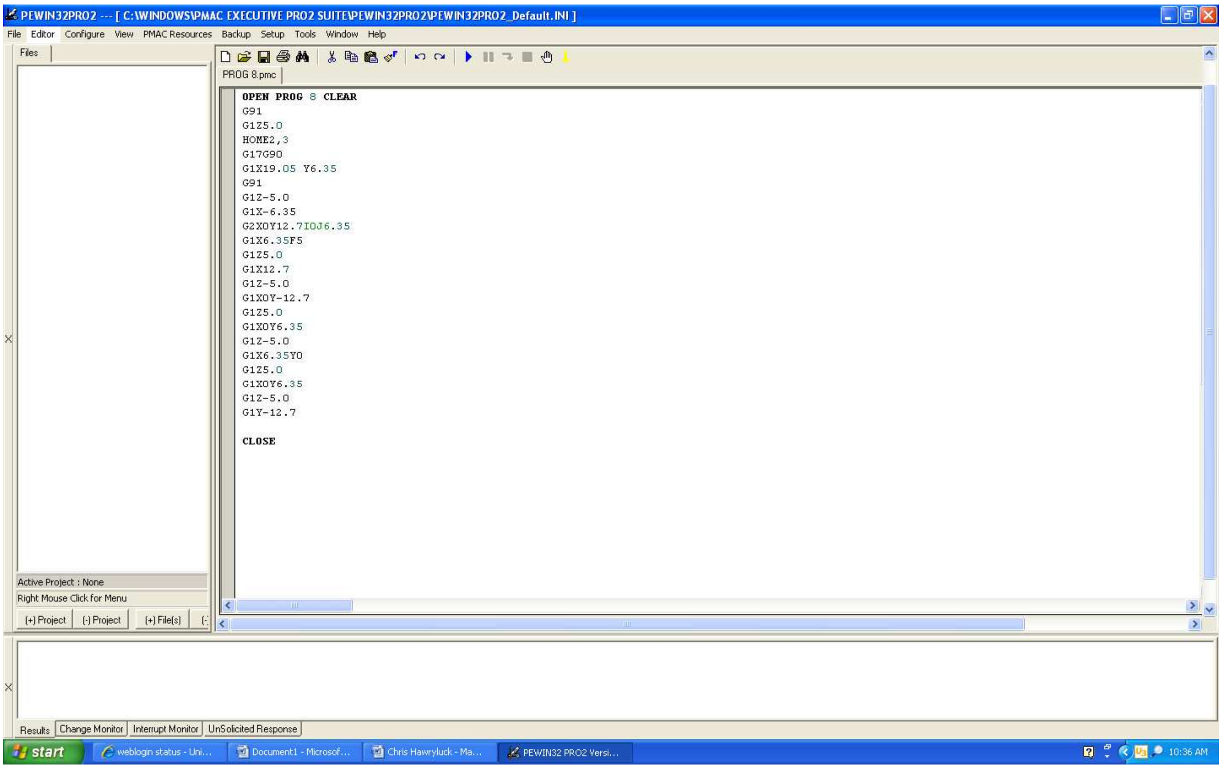
- Go to the File menu and select “Open File” or “New File”



- Type **OPEN [program name] CLEAR**

- Type HOME1,2,3

- Enter your motion program code



- Type **CLOSE**

- Save the file with the extension **[program name**].pmc. For example the program may be named PROG 8.pmc

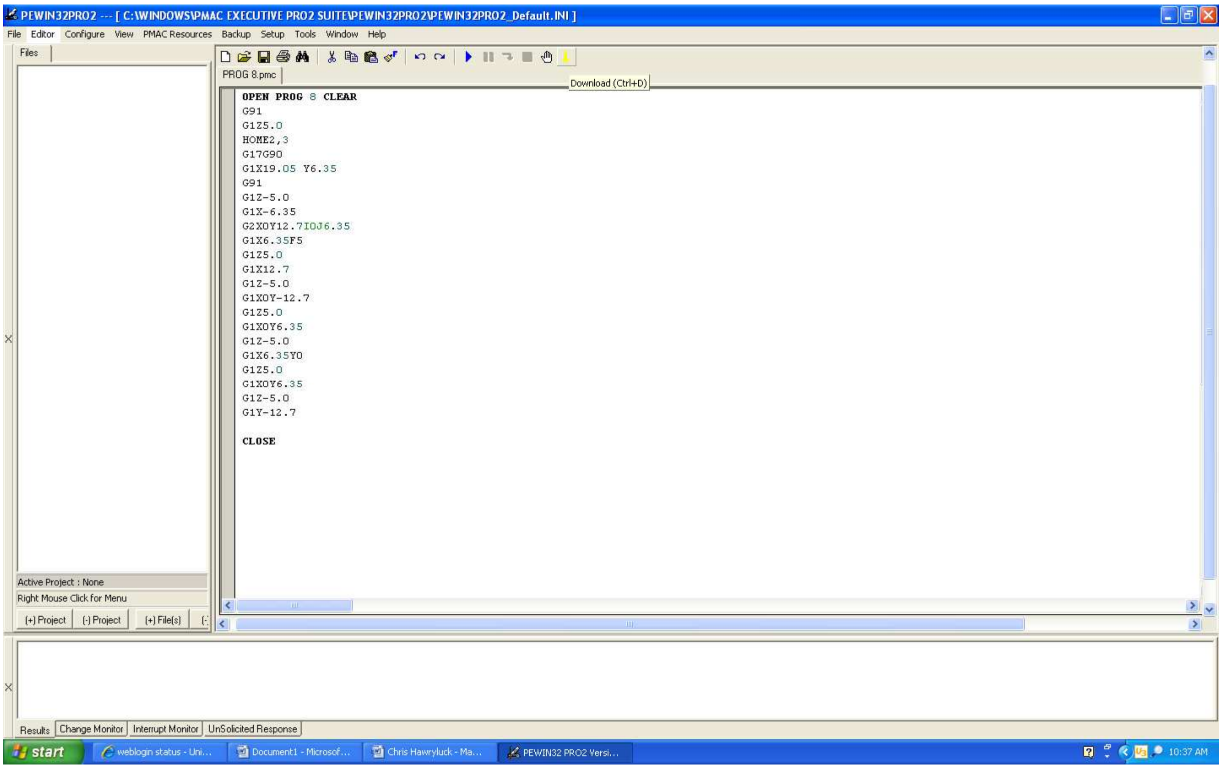
10. To Download a Motion Program

- Open PeWIN32 Pro2 and establish communication with the controller.

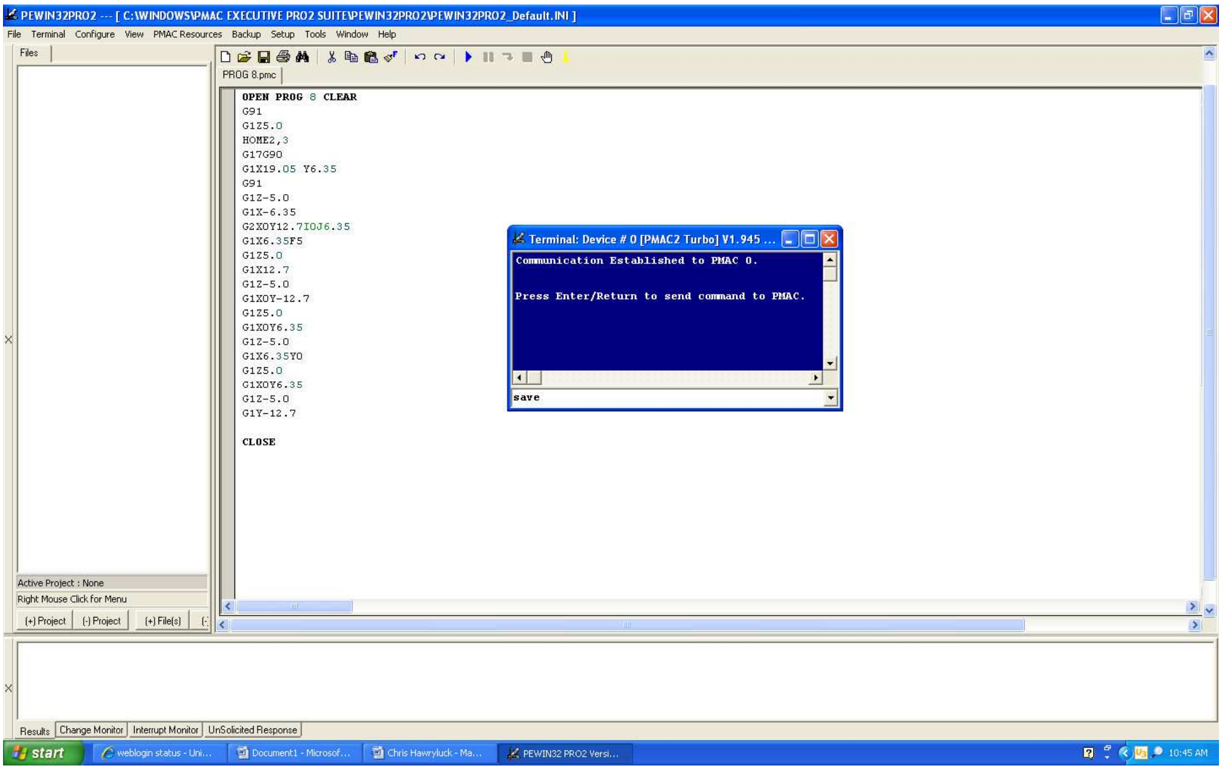
- Suspend any PLCs (**CTRL-D** from the terminal window) or motion programs (**CTRL-A** from the terminal) during a download.

- Once inside the Editor Pro2 submenu in the PeWIN32 Pro2 software:

  - Select download "filename"



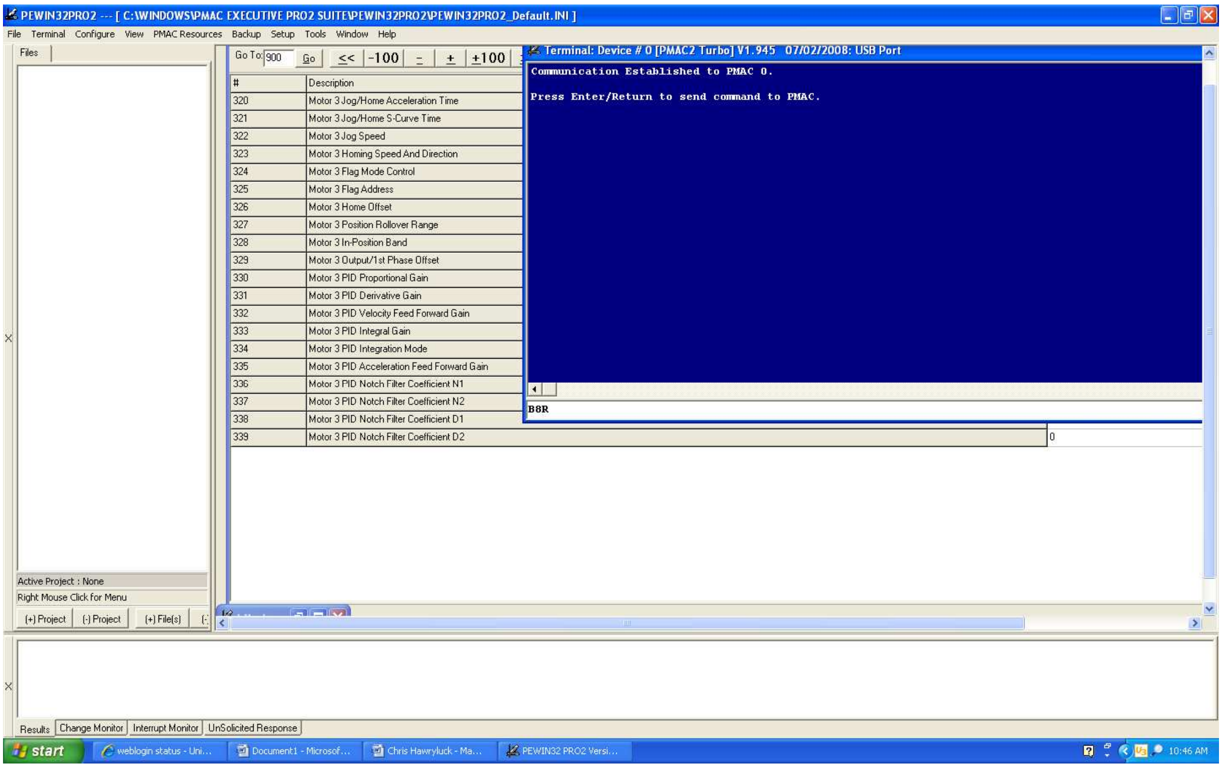
- In the Terminal window, type "save"



11. To Run a Motion Program

- Open PeWin32 Pro2 and establish communication with the controller

- Open the "Terminal" window in the main menu



- Type B**[program name]**R and hit enter.

For example, if the program name is PROG 8.pmc, then type "B8R"

- Machine executes motion program.

12. To Abort a Program

- Once inside PeWIN32 Pro2

a) Open the "Terminal' window

i) Type CTRL-A to abort all programs immediately.

ii) Type "/ " in order to Stop execution at end of currently executing move

iii) Type **"B[{constant}]"** – in order to set program counter to specified location

iv) Type **"H"** in order to hold the feed stage positions

v) Type **"A" to** abort present program or move starting immediately

vi) Type **"ABR[{constant}]" in order to** abort present program and restart or start another program

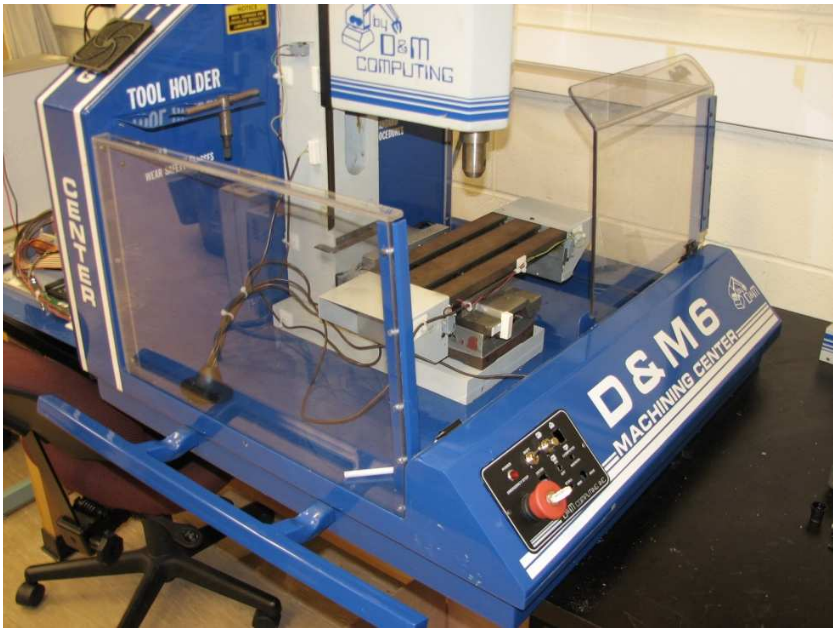
vii) Type **"Q**" in order to halt a program; stop moves at end of last calculated program command.

13. To start the Spindle Motor:

- Open PeWIN32 Pro2 and establish communication with the controller

- Go to the "Terminal" window and type in a value :

    - M402 = Value which is between (300 and 1001). This corresponds to a DAC voltage of 3V (minimum rpm) and 10V (maximum rpm) respectively



- Go to the front of the machine and press the silver push button once.

- Move the Toggle switch downwards to start the spindle.

- Move the Toggle switch upwards to stop the spindle.

13. TroubleShooting:

1) Motors do not shut-off at the end of their respective feed stage travel:

a) Check that the limit switches are operational:

i) Check resistance across the terminals of the Positive and Negative limit switches when the lever is not detent: should read 0 ohms

ii) Check the resistance across the terminals of the Positive and Negative limit switches when the lever is detent: should read infinite resistance

iii) If no to i) and ii), replace switch

b) Check that all terminals are properly connected according to the schematics in Appendix(C)

c) Verify that 12Volts are across terminals 49& 48 of JMACH1 (port on the Turbo PMAC2 Clipper board)

i) If the voltage =0.620V instead of 12V, then check and replace the fuse for the 12V terminal located on the red DC power supply distributor.

2) Feed stages only move in one direction:

a) Check that the Dir(+ and -) terminals are properly connected on JMACH2 (Turbo PMAC 2 Clipper board port) according to the schematic.

b) If yes to a), then check to make sure that the voltage across the Dir(-) terminal and the signal ground reads 0 V.

c) If yes to c), then check the connectivity of the signal ground distributor.

3) Homing command does not work:

a) Check the resistance of the homing switch:

i) When moving base is abutted with the homing switch, resistance should be infinite

ii) Otherwise resistance should be 0 ohms.

b) Check that the homing switch terminals are properly connected on JMACH2 (Turbo PMAC2 Clipper board port).

c) Check that the I-variable, I70n3= 0 in order to that a flag is triggered from the homing switch. "n" corresponds to the number of the motor.

4) Feed stages do not move when issued a Jog command

a) Inside PeWin32 Pro2, go to tools\Tuning Pro submenu and check that the status of Motors 1,2 and 3 are enabled.

Copyright Acknowledgements

1. Hexapod schematic from:

   Blumlein, W. J., The Hexapod. Maschine + werkzeug October 1999.p3

2. Schematic of the Delta robot (from US patent No. 4,976,582)

3. Sketch of the Pentapod Milling Center from:

   Schwaar, M., Stiff pentapod, Design News, Jul.22, 2002, pg41

4. Sketch of the Eclipse Mechanism from:

   Kim, J., Park, F.C. Direct Kinematic Analysis of 3-RS parallel mechanisms. Mechanism and Machine Theory Vol.36 2001, pg 1122.

5. Sketch of Bipolar and Unipolar motor wiring from:

   NMB motor intro pg 82 NMB Technologies. www.nmbtc.com