Design and Fabrication of the MesoMill: A Five-Axis Milling Machine for Meso-Scaled parts

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Introduction

With the increased prevalence of meso-scaled products, new tools are being developed to bridge the gap between fabrication processes tailored for micrometer and millimeter sized features [1] [2]. Compared to its traditional counterpart [3], a small machine tool designed for meso-scale could potentially have a smaller overall footprint, shorter structural loop and lower cost than a conventional machine; in addition, a small machine presents opportunities for improved machine metrology, and easier environmental control. This paper describes the design of the MesoMill: a test machine designed to evaluate the use of components new to the design of machining centers including wire capstan drives, ballscrew splines, and an air bearing spindle with an integral Z-axis.

The MesoMill machine concept is shown in Figure 1 where two ballscrew splines[2] at right angles to each other would provide four degrees of freedom. The air bearing spindle with Z-axis would provide a 5th axis. Ballscrew splines are used in robotic systems for pick and place operations, and at this time, the manufacturer was not aware of a machining application. However, by oversizing the units, their stiffness seemed appropriate. The next challenge is to drive the nuts, which can be done with direct drive at relatively high cost; thus it was decided to investigate the use of a wire capstan drive in order to obtain a backlash-free high stiffness transmission ratio. Figure 2 shows a test stand for one of the ballscrew splines whose nuts are driven by wire capstan drives. The intent was to measure the performance of a single axis, and then if the performance was desirable an entire machine could be created by assembling two such axes.

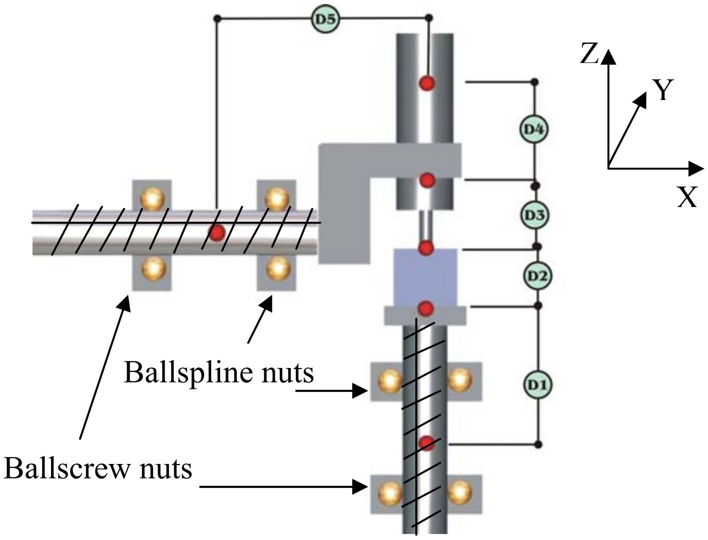

Figure1: Structural Loop of Mesomill: Work path is from the work piece to the center of the nuts (D1-D3), Tool path is from tip of tool to the center of the nuts (D3-D5).

The test stand is currently about 500 mm long, 300 mm wide, and 500 mm high. The machine uses a Westwind air bearing spindle with a speed range of 40,000 to 120,000 rpm [4]. The spindle incorporates a linear machining axis in Z with a travel of 10 mm, and it was obtained from ESI Corp., which uses these spindles for circuit board drilling operations. Position feedback to the PC-based controller is achieved close to the workpiece using a Heidenhain encoder capable of simultaneously measuring both linear and rotary movement. The error

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[2] A ballscrew spline is a shaft that has both helical and axial grooves ground into it for receiving both ballscrew and ballspline nuts

budget for the first prototype estimates a tool path random error of 1.4 μm for the sweet spot and 2 μm with the axes fully extended. The prototype three-axis version of the MesoMill is currently being tested, and a comparison will be presented between the calculated and measured results.

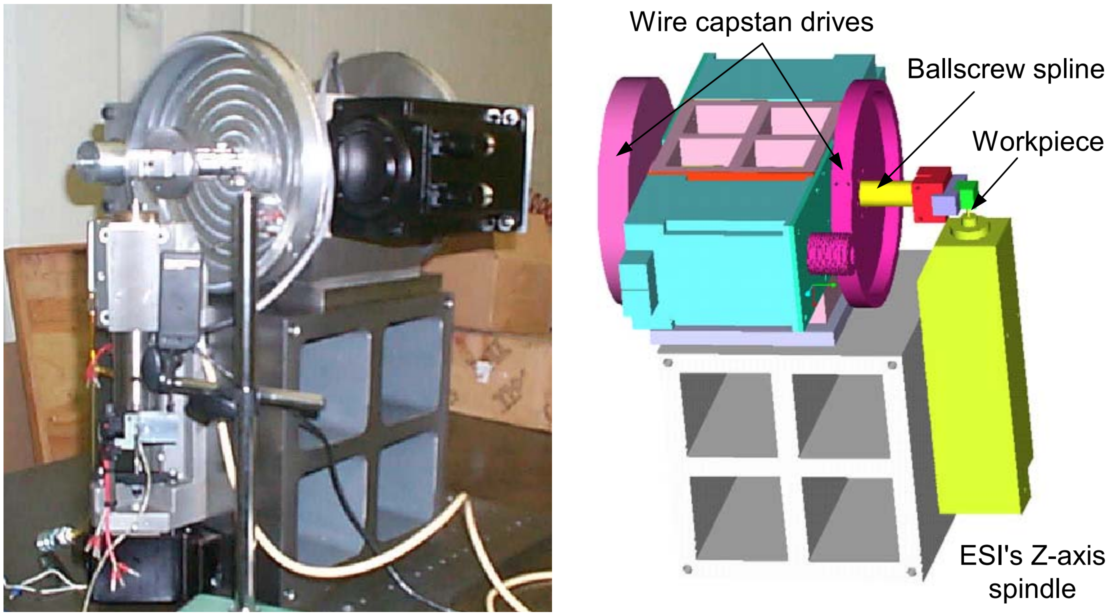

Figure 2: Mesomill single axis test stand and solid model

Error analysis

Given the right angle configuration shown in Figure 1, Tables 1 and 2 show the estimated errors for the work path error and tool path respectively. The largest contributing factor to the error is from misalignment of the tool in the chuck. The farther the Z-axis is extended, the distance D_3, the larger the error. With the Z-axis retracted and the axes centered, the predicted accuracy is 1.4 microns. With all the axes at the limit of their travel, the predicted accuracy is 2 microns. With mapping of the axes' errors, a factor of 5-10 improvement is expected because there are only preloaded low friction joints in the machine.

Table 1: Work path error for retracted and extended tool. Both cases are the same. The zeros indicate no movement in direction specified (nonsenstive direction) and the rotational errors are small. Estimated as one part in 100,000. D_1 to the base is the origin.

Work Path	**Δ_x (μm)**	**Δ_y (μm)**	**Δ_z (μm)**	**ε_x (rad)**	**ε_y (rad)**	**ε_z (rad)**
D_2 (25 mm)	.25	.25	.25	1E-5	1E-5	1E-5
D_1 (230 mm)	.16	.16	0	1E-5	1E-5	1E-5
D_1 to base (216 mm)	0	0	0	0	0	0

Table 2: Tool path error for tool retracted (Retr) and extended (Ext). The zeros indicate no movement in direction specified (nonsenstive direction) and the rotational errors are small. Estimated as one part in 100,000.

Tool Path	**Δ_x (μm)**	**Δ_y (μm)**	**Δ_z (μm)**	**ε_x (rad)**	**ε_y (rad)**	**ε_z (rad)**
D_3 (16 mm) (Retr)	.1	.1	0	1E-5	1E-5	1E-5
D_3 (38 mm) (Ext)	.1	.1	0	1E-5	1E-5	1E-5
D_4 (70 mm) (Retr)	.015	.015	0	1E-5	1E-5	1E-5
D_4 (70 mm) (Ext)	.038	.038	0	1E-5	1E-5	1E-5
D_5 (215 mm) (Retr and Ext)	.5	.5	0	1E-5	1E-5	1E-5
D_5 to base (254 mm) (Retr and Ext)	.15	.15	0	1.02E-6	1.02E-6	1.02E-6

Stiffness Model of the Ballsplines

The principal structural elements are the ballsplines, and originally it was thought that the ballsplines could project through air bearing sleeves in order to provide a greater degree of accuracy and dynamic stiffness. The grooved portion of the shaft could be of a smaller diameter than the portion through the air bearings, and hence radial error motions induced by the nuts could be reduced. Figure 3 shows the model of the this concept [5], and it is found, as the length of c and d increase, the deflection ratio between the workpiece end (x= 0) and the nut end (x = c + d) decrease for a given radial deflection at the nut; however, the size of the machine grows in proportion to its workspace so the question is, how much "self coupling" is desired verses buying more accurate components in the first place?.

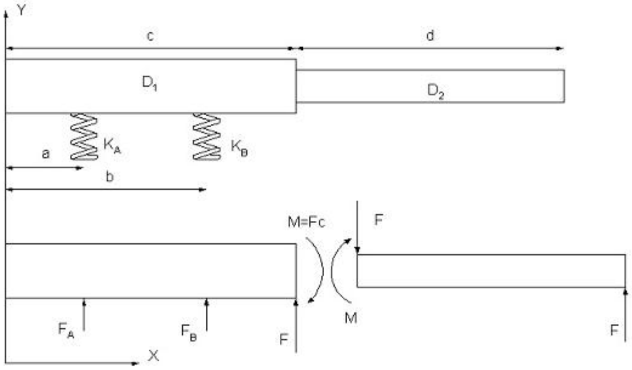

Figure 3: Stepped shaft model of the ballscrew spline supported at its front end by air bearings, where radial displacement from the nut closest to the air bearings is applied to the end of shaft segment D_2.

However, adding length to the shaft to enable it to be supported by the air bearings makes the machine very large with respect to its work volume; hence an important part of the tests are to determine if they are really even needed. Thus the initial test machine does not use the air bearings, it only uses the screw and spline nuts to support the shaft.

Transmission System

Wire capstan drives are used as rotary transmission elements for their antibacklash and high stiffness properties, which can be on the order of 10^5 N-m/rad. The multiple wrappings of the cable around the drum are the key in giving the transmission its stiffness [6]. The capstan considered in this study is made up of two drums, 76 mm input and 280 mm output, and a 3 mm diameter cable. The cable is wrapped around the drum in a figure-eight pattern twice but could be wrapped more to obtain even higher stiffness. There are several ways to analyze the stiffness of the transmission depending on how friction is considered. Figure 4 figuratively shows the cable wrapping scheme of the wire capstan drive.

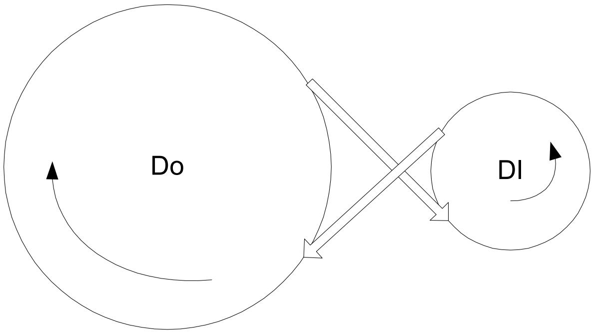

Figure 4: Representation of Capstan drive where arrows represent direction of drum and cable motor

The cable can exhibit traction along a particular section, or along the whole drum. These two derivations were performed and showed the stiffness is higher for the traction acting along the drum instead of a particular section. However, even though the stiffness is smaller, it is still higher than similarly sized belt or gear transmissions. Experiments were conducted to determine the stiffness of a capstan drive. These measurements show a stiffness value less than 10^5 N-m/rad, but as the preload in the cable is increased, the stiffness increases too as is shown in Figure 5.

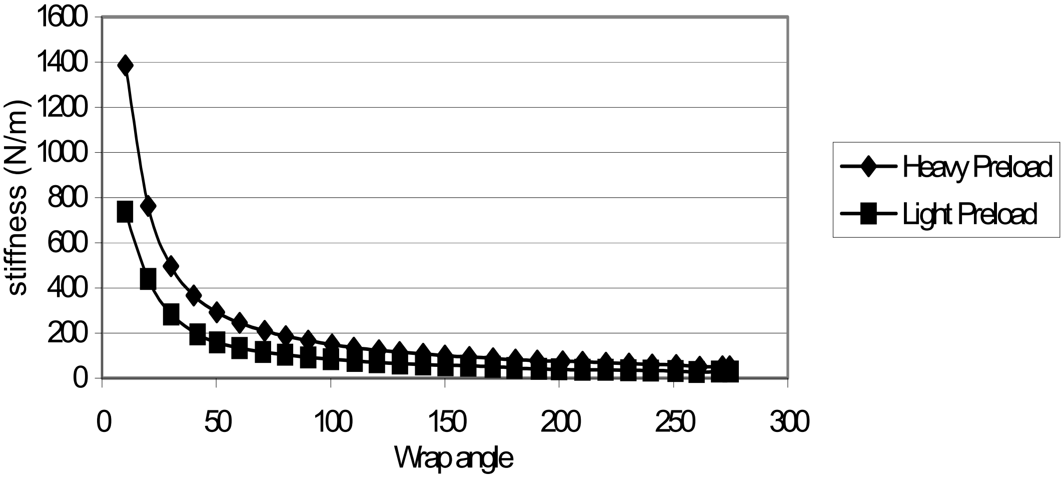

Figure 5: Measured stiffness vs. angle of rotation for heavy and light preload.

Conclusions

The mesomill testbed has been assembled and is currently being integrated with the control system. Preliminary experiments on the stiffness of the wire capastan drives are very encouraging. The general ease with which the components were assembled makes us optimistic about the obtainable repeatability and accuracy of the system.

Acknowledgements

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References

[1] Proceedings of the *Manufacturing Three-Dimensional Components and Devices at the Meso and Micro Scales: A Workshop Cosponsored by the National Institute of Standards and Technology and the National Science Foundation,* Gaithersburg Maryland, 1999

[2] National Science Foundation workshop on M^4: Micro/Meso-Mechanical Manufacturing. Northwestern University: Evanston, IL, May 2000. http://216.239.53.100/search?q=cache:gGx0lQtiaTMC:www.mech.northwestern.edu/MFG/AML/M4/M4-Files/M4-REPORT.doc++site:www.mech.northwestern.edu+machines+meso+Illinois&hl=en&ie=UTF-8

[3] ROBOTOOL-Project, *Advanced Kinematics for Manufacturing Applications: List of existing parallel kinematics*. Last updated July 9, 2002. http://www.ifw.uni-hannover.de/robotool/pages/listeenglisch.htm

[4] ASME B5.57M *Methods for Performance Evaluation of Computer Numerically Controlled Lathes and Turning Centers*, version 9.0, May 1997, ASME B5/TC52 Committee.

[5] Roberts, Michael, *Approximation of Air Bearings as Linear Point Springs: Verification of an Analytical Model for a New Five-Axis Machine Tool*. Massachusetts Institute of Technology, 2002.

[6] Sagebrush technology, Inc. Date visited 12/2002. http://www.sagebrushtech.com/tech/technology.html