

Premachining computer numerical control contour validation

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The current procedure followed to manufacture a new part by computer numerical control (CNC) machining is to write the part program, machine a test part, and measure the test part for conformance to the required dimensions and tolerances. If the test part dimensions are incorrect, the part program is modified, and the process is repeated until a successful part is machined. In many applications, such as the aerospace industry, where material cost and machining time are high, this iterative process becomes economically unacceptable. Research has been conducted to test the feasibility of using the laser ball bar (LBB), a spatial coordinate measuring device, to measure dynamic continuous path contours of CNC part programs to micrometer accuracy before machining. In this way, a virtual test part can be measured and compared to the design drawings to validate the CNC part program. This reduces or eliminates the costly and time-consuming steps involved in the machining of physical test parts. This paper outlines the testing method and results acquired using one LBB to measure dynamic part paths employing sequential trilateration. A circular contour was measured using an encoder trigger for data capture. The radial error motions of the spindle used to generate the circular contour were also measured using a capacitance probe nest to verify the LBB results. Comparable error waveforms between the LBB and cap probe measurements verified the possibility of using the LBB to measure dynamic continuous path contours. Future work using three LBBs simultaneously is also outlined. © 1998 Elsevier Science Inc.

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Introduction

One of the most important uses of computer numerical control (CNC) machine tools is the cutting of complex continuous part paths or contours. In continuous path numerical control systems, there is contact between the cutting tool and workpiece throughout the part path while up to five axes are in motion. Therefore, the final workpiece dimensions are directly related to the

positional relationship between the tool and workpiece. The ability to monitor this relationship and predict the final part dimensions is important for today's manufacturing engineer.

For a new part or production run to be manufactured with the use of CNC machine tools, the current procedure is to write the CNC part program using the engineering drawings, execute the part program to machine a test part or prototype, and then inspect the test part, normally with the aid of a coordinate measuring machine (CMM), to check for conformance to design tolerances. This feedback of the actual part dimensions (with an adequate degree of precision) is currently the only way to certify the performance of the CNC pro-

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gram. If the test part does not meet the specified tolerances, as is often the case for a first trial, the CNC program is modified, another test part is machined, and the process is repeated.

This iterative process may be acceptable, although inefficient, in situations where the material is inexpensive and machining time is short. However, in many cases, such as the aerospace industry, the material is costly (expensive forgings to be machined) and machining time is dramatically increased. In such instances, this iterative process of producing dimensionally correct parts becomes economically unacceptable.

Both time and money could be saved if there were a direct way to measure the machine tool's dynamic contouring accuracy over an arbitrary three-dimensional (3-D) path without the need to machine an expensive test part. At the same time, the efficiency of the CNC machining process could be greatly increased. The use of the laser ball bar (LBB), a spatial coordinate measuring device, to take dynamic measurements of a path could reduce or replace the need to machine and inspect a test part. In effect, the spatial coordinates of the dynamic tool path measured by the LBB could function as a virtual test part.¹

This particular approach must be differentiated from the conventional approach to machine tool metrology. At this time, the normal procedure is to measure the machine tool error motions including geometric, thermal, and, perhaps, process errors. These errors may then be used as premachining compensation in the machine tool controller in an effort to give theoretically perfect motions. The machine's accuracy and, therefore, the part dimensions are based largely on the success of this time-consuming process. Although this research is certainly not a replacement for this body of work, it is also not the same. The purpose of this work is to try to predict the final part dimensions for the execution of a specific CNC part program on a given machine tool prior to cutting the part, not to measure the geometric or servo errors of the machine tool.

Background

One of the main categories in the modern evaluation of CNC machining centers is the assessment of the contouring capabilities of the machine tool. The evaluation of this contouring accuracy can be divided into two main classifications: postprocess and in-process testing.

Postprocess testing includes those tests performed after machining has been completed. The most popular postprocess inspection tool is the

CMM. Other postprocess methods used to evaluate a CNC machine tool's contouring accuracy involve the use of either master parts or well-defined contours. One example of this technique is the use of standard part paths, such as the part program corresponding to the National Aerospace standard test part 979 (NAS 979), to machine a master part. This part can then be measured to evaluate flatness, squareness, parallelism, roundness, etc. A similar, but somewhat more efficient method has been termed "master part tracing." This procedure simulates machining by replacing the tool with a gauge and the workpiece with a master part of known accuracy. The machine is then programmed to follow the ideal path given by the master part. Deviations from the ideal path registered by the tool gauge represent the contouring error.^{2,3}

The other main type of contour measurement is in-process testing. This category can then be subdivided into in-process and in-cycle gauging. In-process gauging refers to testing carried out during the actual machining process; whereas, in-cycle gauging defines measurements taken after the part is finished but before it is removed from the machine.

In-process gauging is generally achieved by adding analog transducers to the machine tool to assess the test part's size directly during the cutting operation. An example of in-process measurement, the so-called workpiece-referred form accuracy control (WORFAC), has been suggested by Uda et al.⁴ It consists of a highly sensitive optical surface sensor and a microtool servo to adjust for changes in the distance between the tool holder and workpiece. Although accuracy improvements were shown with the use of this feedback system, it is still limited to simple geometries (cylindrical turning operations) and requires complex tooling and setup.

In-cycle gauging can be accomplished by replacing one or more of the tools in a CNC machining center's turret with measuring probes. These probes can then be indexed into the tool position to probe key features of the test part while it remains in the machine and, unfortunately, is still in a thermally unstable state.

An adaptive error correction method has been proposed by Mou et al., which combines both in-cycle and postprocess testing with a geometric-thermal error model.^{5,6} This technique proposes the use of in-cycle and postprocess gauging to determine interactively the changes in the geometric-thermal model over time.

Although these processes provide worthwhile means of evaluating a CNC machine tool's con-

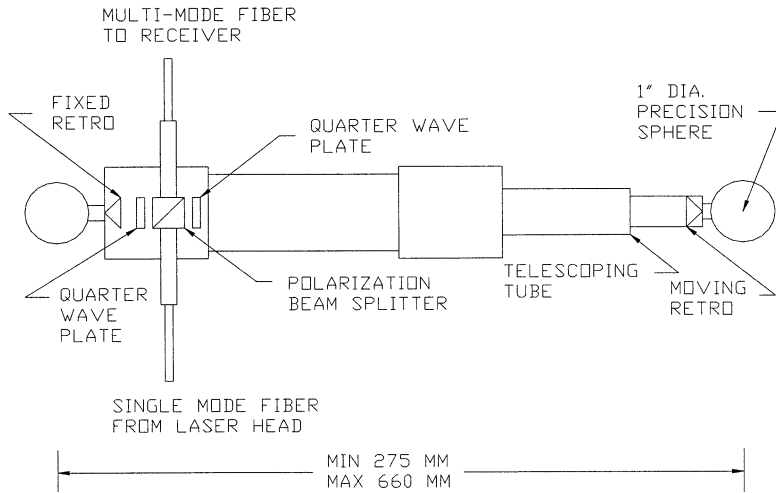


Figure 1 Laser ball bar

touring accuracy, they all suffer from the necessity of machining and inspecting a test part for conformance to required tolerances. The purpose of this research was to investigate the possibility of using the LBB as a measurement tool to determine this CNC path accuracy without the need to produce a costly test part. Some commercial products moving toward this goal include the Heidenhain two-dimensional (2-D) grid plate and Renishaw ball bar. These tools, however, are path limited. The ball bar allows only circular or hemispherical paths and records only radial deviation.

The grid plate can measure only planar part paths. For 3- or 5-axis part paths, the LBB system is required to measure these contours dynamically.

Laser ball bar

The LBB is a precision linear displacement measuring device developed by Ziegert and Mize at the University of Florida.⁷ It consists of a two-stage telescoping tube with a precision sphere mounted at each end. A heterodyne displacement measuring interferometer is aligned inside the telescop-

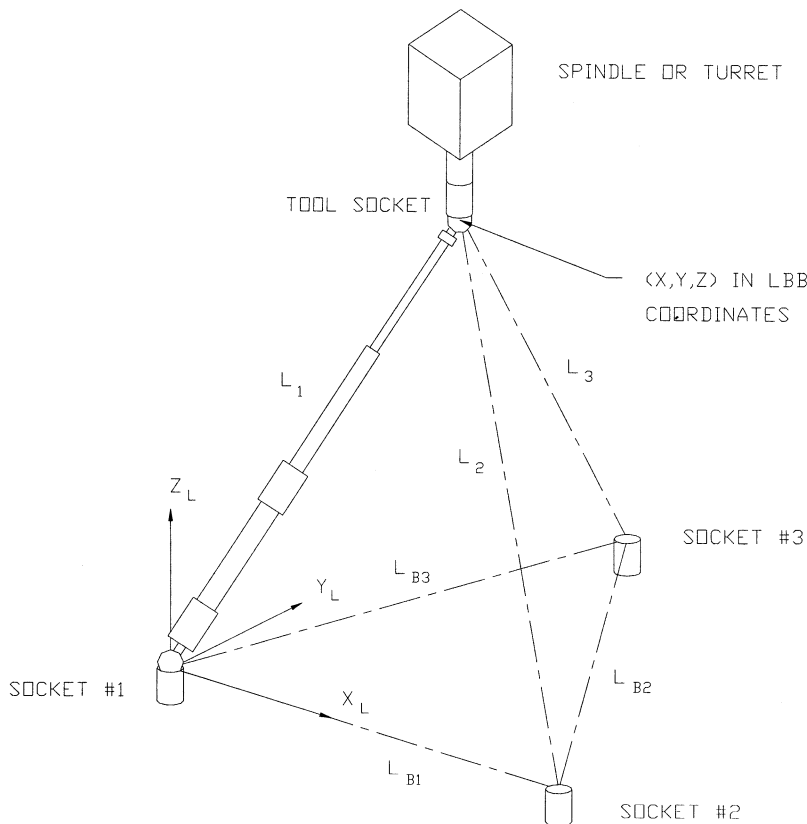
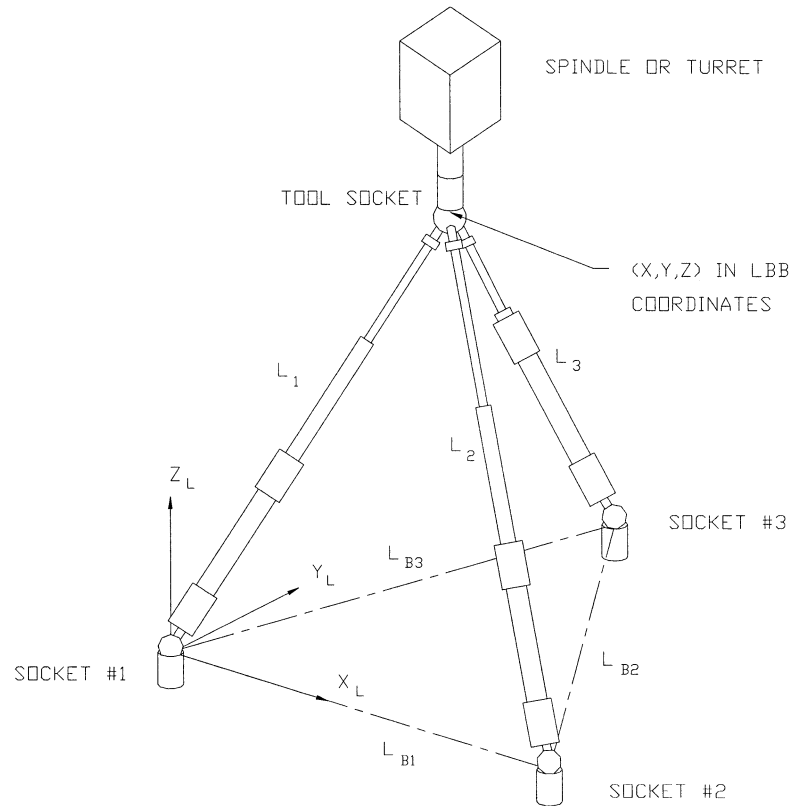


Figure 2 Sequential trilateration

Figure 3 Simultaneous trilateration

ing tube and measures the relative displacement between the two spheres (see *Figure 1*). The LBB has been shown to be accurate to submicrometer levels during static measurements of spatial coordinates.⁸

Once initialized, the LBB uses trilateration to measure the spatial coordinates of points along a CNC part path. The six sides of the tetrahedron formed by three base sockets (attached to the machine table) and a tool socket (mounted in the spindle) are measured, and the coordinates of the tool position can be calculated geometrically.

In sequential trilateration, the same part path is traversed three times, measuring the lengths of one of the base-to-tool socket legs at a finite number of points during each repetition (*Figure 2*). Note that the tool socket must be in exactly the same position (for a given point) for each of the three measurements. If the tool socket were in a slightly different position at point 5 for leg 3 measurement than for legs 1 and 2, for example, the spatial coordinates calculated by trilateration would be incorrect. To achieve accurate coordinate measurements, the sampling trigger must be spatially repeatable. When quasistatic measurements are performed; i.e., the tool stops at each measurement position, the machine repeatability governs the accuracy at the measured coordinate. For most machine tools, the short-term repeatabil-

ity is substantially better than the absolute positioning accuracy, and this process yields satisfactory results. However, for dynamic path measurements, the LBB must be triggered at specific points along the path to collect data.

In simultaneous trilateration, three LBBs ride on a single sphere at the tool point to completely define the tetrahedron with one execution of the CNC program. For this method, because all three leg lengths are captured simultaneously, the spatial repeatability of the sampling trigger is no longer a concern. *Figure 3* illustrates this method. The tool socket shows the three individual LBBs, each using a three-point contact magnetic socket, attached to a single sphere. To minimize interference between the three magnetic sockets as they move over the sphere surface and to ensure an adequate range of motion, the socket diameters (and consequently the neodymium magnet diameters) must be relatively small. This requires minimization of the LBB weight.

The actual tool point positioning errors collected by the LBB can then be used in conjunction with a suitable kinematic model to evaluate the overall parametric accuracy of a machine tool. These off-line error measurements can provide precalibration compensation when stored in the machine tool controller and used to correct the

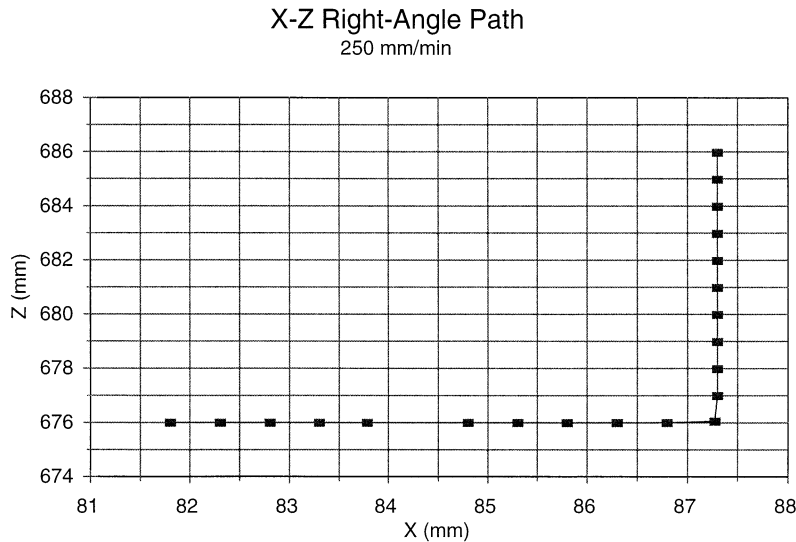


Figure 4 250 mm/min test

commanded position according to its location in the work volume.

The parametric error map for a 3-axis milling machine was constructed by Kulkarni using both the LBB technique and the standard methods described in the ASME B5.54 Standard, "Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers."⁹ The agreement between the two results verified the LBB method.¹⁰ A second study by Srinivasa measured the positioning errors on a 2-axis turning center over a thermal duty cycle and correlated these errors with the temperature gradients within the machine tool using a neural network. A PC-based error compensation system was then used to compensate for the errors predicted by the neural network.¹¹

The above methods give a rapid, efficient way to measure the quasistatic errors of a machine tool and, thus, evaluate its static positioning accuracy. However, these methods do not characterize the dynamic positioning accuracy of the machine tool.

Dynamic path measurements

The purpose of this research was to appraise the dynamic measurement performance of the LBB to evaluate its potential for use in dynamic path measurements. Because only one LBB was available at the time of study, it was decided to test the feasibility of using sequential trilateration to perform these measurements. In other words, it was desired to measure the spatial coordinates of the tool point at predefined intervals along the contour during the execution of the CNC part program while the machine was in motion using one LBB. These dynamic path measurements using a single LBB require that the three leg lengths from the

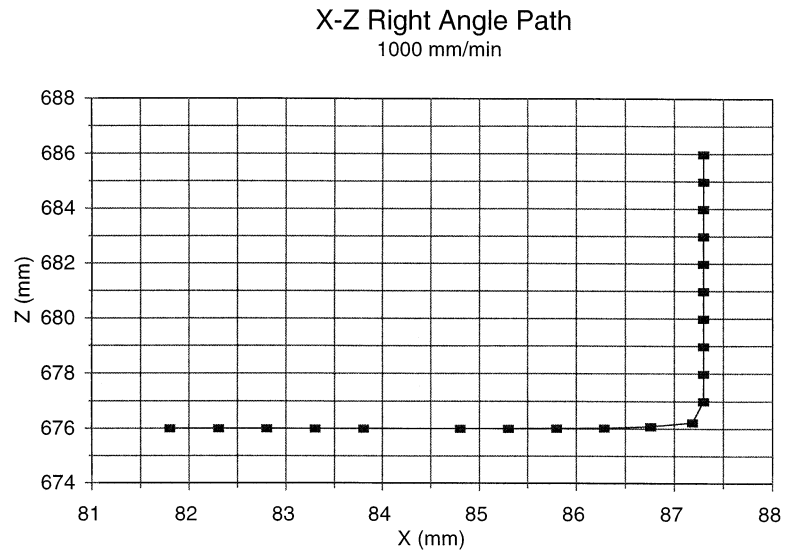
base sockets to the tool socket are acquired as the tool passes through the same points along its path on three consecutive runs. This necessitates a spatially repeatable triggering method to initiate data capture.

Two separate techniques were implemented and tested to provide the repeatable measurement trigger. The first sampling procedure used a time-based scheme. In this method, a sample was taken at the start of the motion, and then consecutive samples were taken at well-defined time intervals (every 5 ms) throughout the part path. This method was shown to be unacceptable, because the acceleration profile of the controller varied slightly from run to run on the two-axis turning center used in this study. This caused the tool to be in a slightly different position (up to 15 μm at 1000 mm/min) along the path during each leg measurement.

The second triggering scheme involved the use of the feedback signals from the machine axis encoders. In this method, the axis encoders were continuously sampled, and the length of the LBB was recorded at discrete distance intervals along the part path. This sampling method was chosen, because the positioning repeatability (and therefore, the encoder output) is the smallest source of error in the contouring performance of a machine tool.

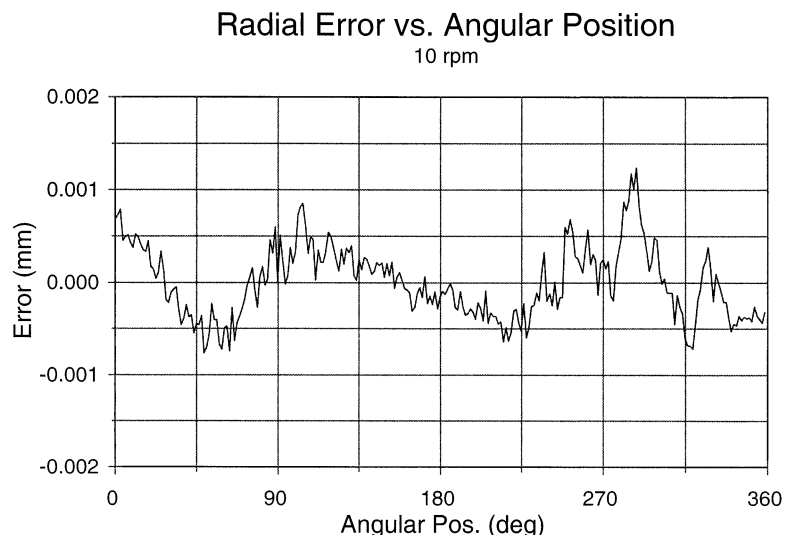
Results

Initial dynamic path measurements using the X- and Z-axis encoder sampling algorithm were completed for both right angle and semicircular contours. A look-up table of encoder positions for each path was constructed. During measurements, the X and Z encoder positions were continuously

Figure 5 1000 mm/min test

sampled and a datapoint was captured (with a repeatable $200 \mu\text{s}$ delay) when the encoder positions matched the values in the look-up table. Experimental results showed general path degradation with higher velocities. This path degradation was especially evident for the right angle contour. *Figures 4 and 5* show measurement results for path velocities of 250 and 1000 mm/min, respectively. (The missing point in the data is because of an error in the look-up table.) At velocities of 1 m/min and higher, the corner was increasingly rounded because of the inherent steady-state positional error, or velocity lag, in the positional servo. The velocity lag, which is proportional to the feed rate, causes the commanded motion to be executed with a slight delay. In an X - Z right angle motion, for example, this gives the X motion time to decelerate and stop before the Z motion starts. This effectively eliminates overshoot, but can also round the corner at higher velocities.

Because the actual part path for the right angle contour changed as the feed rate was increased, it was impossible to distinguish between path errors caused by the controller (caused by the velocity lag) and any measurement errors introduced by the LBB. Therefore, to provide a contour that would be independent of velocity, the spatial coordinates of a circular contour provided by the spindle rotation with a socket mounted off center were measured by sequential trilateration. The circular path, 20.8 mm in diameter, traced by the socket as the spindle rotated was divided into 256 parts. An LBB datapoint was taken every four spindle encoder counts (1024 counts/revolution for the spindle encoder gave 256 datapoints). The path velocity (spindle speed) was then varied for consecutive tests to investigate the dynamic measurement performance of the LBB. The radial error motions for spindle speeds of 10 and 60 rpm

Figure 6 10 rpm LBB test

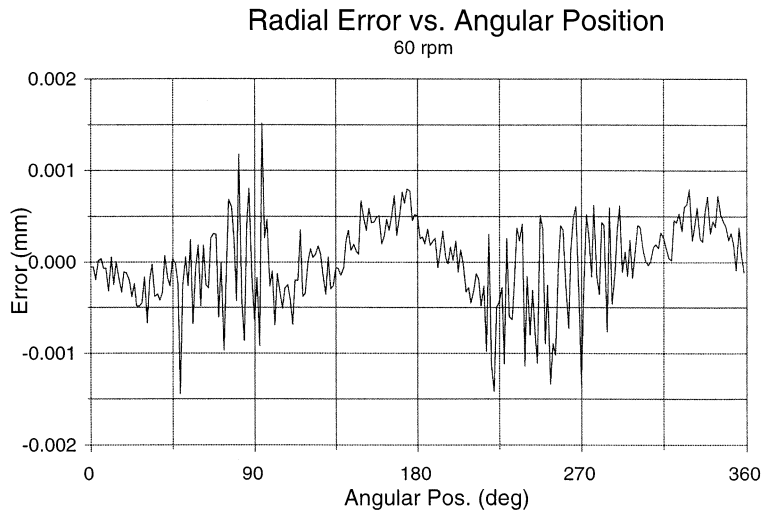


Figure 7 60 rpm LBB test

(tangential velocities of 653 and 3921 mm/min) are shown in *Figures 6 and 7*.

From these results, it can be seen that the radial error fits approximately within a $\pm 1 \mu\text{m}$ band with some noise. The seemingly smoother waveform at the slower spindle speed is caused by aliasing at the lower sampling rate (note that the sampling rate is directly proportional to the spindle speed). The cause of the repeatable seemingly asynchronous waveform with some superimposed high-frequency noise was not immediately apparent. Possible sources, such as spindle motion errors, machine noise, precision sphere/three-point socket alignment errors, or bearing friction in the LBB, have been suggested.

To validate the LBB results, the spindle error motions were measured at the same feed rates (but higher sampling frequencies) using two mu-

tually perpendicular capacitance probes and a precision artifact¹² and compared to the radial error motions attained by the LBB tests. A grade 5, 1 in. diameter test ball was attached magnetically to a three-point contact socket. This socket was attached to a wobble plate clamped in the spindle chuck. The radial error motion for a 60 rpm test using this method is shown in *Figure 8*.

A comparison of this result with the data obtained using the LBB for the same speed shows that both error motions fit approximately within a $\pm 1 \mu\text{m}$ band, and both exhibit seemingly asynchronous motion, although it is difficult to define the period of the waveform with only one revolution of data. Although this error range is at the limit of the LBB accuracy, the waveforms were similar, and there were no additional errors (beyond the $\pm 1 \mu\text{m}$ band) introduced by the LBB

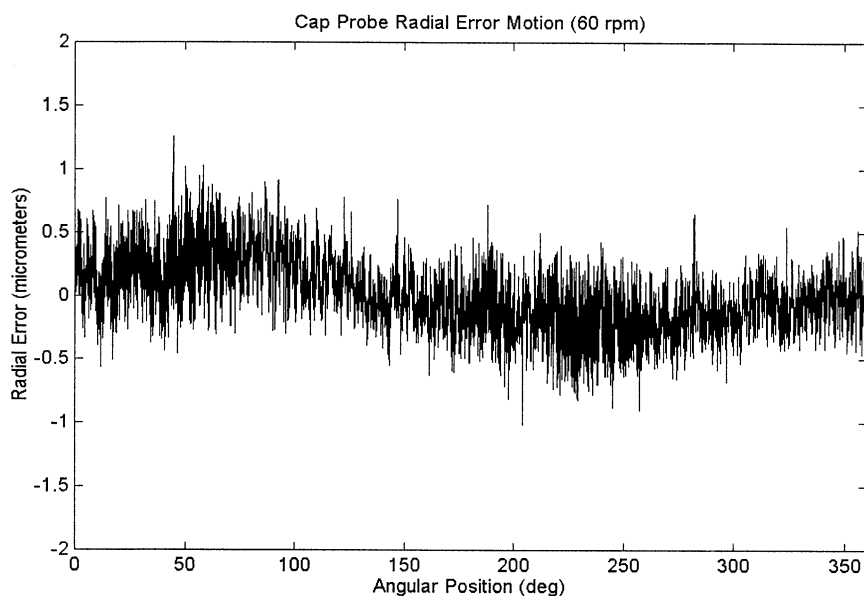


Figure 8 Capacitance probe spindle error motions

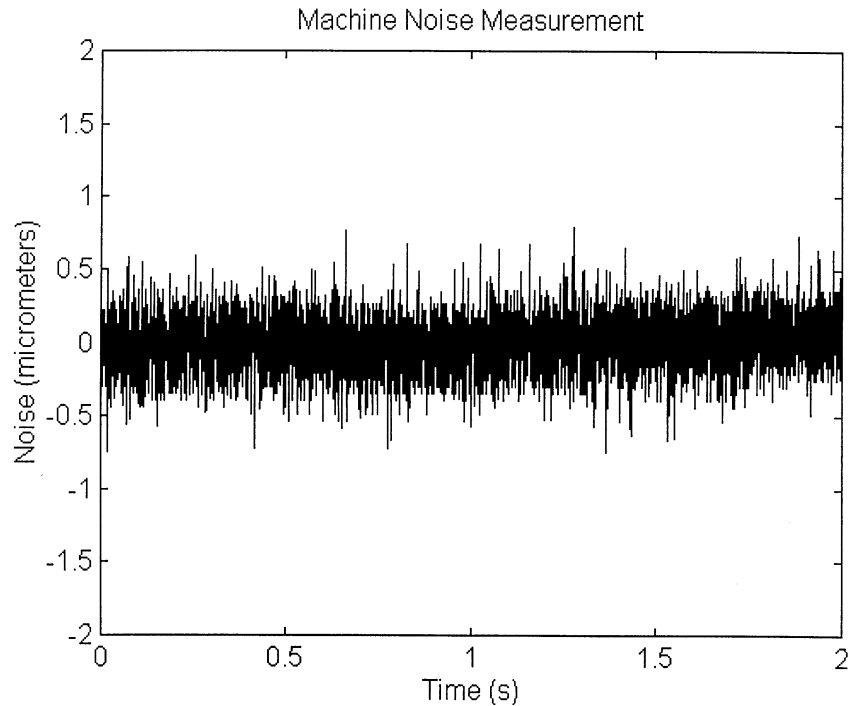


Figure 9 Machine noise measurement

measurements. These results suggest that the LBB is a suitable dynamic measuring device.

To explore the possible sources of the 120-Hz high-frequency noise found in both tests, measurements were taken using the cap probe nest to sample the sphere movements with the machine on, but no spindle motion. Data were collected at a rate of 20 kHz for a period of 2 sec. The result of these measurements showed a random noise level of $\pm 0.5 \mu\text{m}$ at the same 120-Hz frequency seen in the LBB and capacitance probe tests. It should be noted that the high-frequency noise content is more evident in the cap probe test simply because the sampling frequency was much higher, and the possibility of aliasing is reduced. The results of this test are shown in *Figure 9*.

Conclusions

Experimental results show that the LBB is a suitable device for dynamic path measurements, because the magnitude and waveform of the radial error motions measured with the LBB corresponded to those recorded using the cap probe nest for the 2-D circular part path. Although the magnitude of these error motions is at the limit of the LBB accuracy, the fact that no additional errors were introduced by the LBB, and the similarity in the measurements (taking sampling rates and the possibility of aliasing into account) suggest that the LBB is suitable for dynamic measurements. Dynamic measurements of 3-D CNC tool paths, or virtual test parts, could also be completed

and used to validate the conformance of the CNC part program to the required engineering specifications.

The ultimate goal of this research was not to predict the machine tool geometric or servo errors, but rather to predict the final dimensions of a part for a specific CNC program on a given machine. This paper evaluates the LBB as a potential tool to perform these measurements. Most of the difficulties encountered in this work were caused by the necessity of sampling the LBB length at exactly the same points in space for the three tool-to-base socket measurements during three consecutive runs. Despite this difficulty, the experimental results indicate the LBB holds promise as a tool for dynamic measurement of arbitrary 3-D tool paths.

Future work includes modifying the LBB design to allow simultaneous trilateration using three LBBs. This would permit the simultaneous capture of all three leg lengths at a finite number of points during a single execution of the part program and would eliminate the sampling and timing issues. In this configuration, a time-based scheme would then be suitable, because all three leg lengths are recorded simultaneously, and small changes in the controller acceleration profile from one run to the next would no longer be a concern.

Additionally, a cutting-force model could be added to the measurement algorithm to refine the predicted part dimensions as a function of both the measured path coordinates and the applicable

cutting forces. The cutting-force model could act as a filter to postprocess the measured data and predict the final part dimensions. The virtual test part dimensions could then be validated by comparison to actual machined test parts. Once the implementation of simultaneous trilateration using three LBBs is completed, the next step will be to compare measured path coordinates with the machine tool coordinates (collected simultaneously) in an effort to correct any errors in the numerical control program.

References

- 1 Schmitz, T. "Machining virtual test parts." M.S. thesis, University of Florida, Gainesville, FL, 1996
- 2 Tlusty, J. and Koenisberger, F. "Specifications and tests of metal cutting machine tools, Vol. 1," Proceedings of the Conference, University of Manchester, Institute of Science and Technology, Manchester, UK Feb. 19, 20, 1970, 45–49
- 3 Bryan, J. B. and Pearson, J. W. "Machine tool metrology," TP IQ68-753, ASTM, 1968
- 4 Uda, Y., Kohno, T. and Yazawa, T. "In-Process measurement and workpiece referred form accuracy control system (WORFAC): Application to cylindrical turning using an ordinary lathe," *Prec Eng*, 1996, **18**, 50–55
- 5 Mou, J., Donmez, M. A. and Cetinkunt, S. "An adaptive error correction method using feature-based analysis techniques for machine performance improvement, Part 1: Theory derivation," *Trans ASME*, 1995, **117**, 584–590
- 6 Mou, J., Donmez, M. A. and Cetinkunt, S. "An adaptive error correction method using feature-based analysis techniques for machine performance improvement, Part 2: Experimental verification," *Trans ASME*, 1995, **117**, 591–600
- 7 Ziegert, J. C. and Mize, C. D. "Laser ball bar: A precision instrument for machine tool metrology," *Prec Eng*, 1994, **16**, 259–267
- 8 Mize, C. D., Ziegert, J. C., Pardue, R. and Zucker, N. "Spatial measurement accuracy tests of the laser ball bar," Final report for CRADA No. Y-1293-02244 between Martin Marietta Energy Systems and Tetra Precision, Inc., August 1994
- 9 ASME B5.54. *Methods for Performance Evaluation of Computer Numerically Controlled Machining Center*. New York: American Society of Mechanical Engineers, 1992
- 10 Kulkarni, R. "Design and evaluation of a technique to find the parametric errors of a numerically controlled machine tool using a laser ball bar," M.S. thesis, University of Florida, Gainesville, FL, 1996
- 11 Srinivasa, N. "Modeling and prediction of thermally induced errors in machine tools using a laser ball bar and a neural network," Ph.D. dissertation, University of Florida, Gainesville, FL, 1994
- 12 Tlusty, J. "System and methods of testing machine tools," *Microtecnic*, 1959, **XIII**, 166–167