92

Sensor Fusion Method for Machine Performance Enhancement

SAND--98-8499C
CONF-980548--

Jong-I Mou
Department of I&MSE
Arizona State University
Tempe, Arizona

Calvin King, Robert Hillaire
Integrated Manufacturing Systems Center
Sandia National Laboratories
Livermore, California

Steven Jones, Richard Furness
Scientific Research Laboratory
Ford Motor Company
Dearborn, Michigan

ABSTRACT

A sensor fusion methodology was developed to uniquely integrate pre-process, process-intermittent, and post-process measurement and analysis technology to cost-effectively enhance the accuracy and capability of computer-controlled manufacturing equipment. Empirical models and computational algorithms were also developed to model, assess, and then enhance the machine performance.

INTRODUCTION

In anticipation of the future of manufacturing technology, when machine tools are equipped with open-architecture controls and advanced sensing technology, the information from these sensors must be processed and used to make adjustments at the machine level to produce high quality parts. In order for this vision to be realized, it is necessary to develop analytical models between dimensional measurement sensor data and the factors that result in increased process variations. These models need to be developed from in-depth analysis encompassing advances in machine tool metrology, dimensional metrology, and process control.

The focus of this study was to develop a sensor fusion methodology that uniquely integrates pre-process, process-intermittent, and post-process measurement and analysis technology to model, assess, and then enhance the machine performance in producing parts. The ultimate goal is to make high quality parts with the least amount of scrap. The objective was accomplished by integrating dimensional measurement and inspection analysis functions with machining functions, providing on-line quality analysis and feedback, and developing methods of using sensor data to perform real-time adaptive sensor feedback process controls to reduce overall product variations.

The developed sensor fusion algorithms are implemented on a PC-based open-architecture controller to receive information from various sensors, assess the status of the process, determine the proper action, and deliver the command to actuators for task execution. This will enhance a CNC machine's capability to produce workpieces within the imposed dimensional tolerances.

METHODOLOGY

The method for achieving the goal is to develop sensor fused intelligent machines and processes for precision product realization. The approach is (1) using deterministic modeling technique to derive models for machine performance assessment and enhancement, (2) adopting sensor fusion methodology to identify the parameters of the derived models, and (3) developing open-architecture control environment to adaptively enhance the machine performance.

The developed sensor fusion methodology will integrate and interpret the sensory data collected from pre-process characterization, process-intermittent probing, and post-process inspection to derive a robust and effective machine performance enhancement model. In this paper, the concept of integrating sensor fusion methodology with open-

architecture controller for machine performance enhancement is demonstrated.

Pre-process measurements are those made on the manufacturing process itself in order to characterize the machines, derive appropriate process plans, and delimit process capability [3, 7]. Calibration and correction of machine tools and measuring machines fall in this category. The ANSI B5.54 standard [1] that includes tests for environmental sensitivity, displacement accuracy, spindle errors, thermal errors, kinematic errors, and cutting performance, has been used for the evaluation of the performance of a machine tool [2, 5, 6]. The major assumption is that these errors are both repeatable and predictable so that an error model can be developed to compute those errors.

Process-intermittent measurements are where the manufacturing process is momentarily halted, measurements are made on the part, and those measurements are used to modify process variables. To increase the efficiency of dimensional inspection, industry is attempting to measure the workpiece dimensions during the production process itself; that is, while the workpiece is still on the machine [12, 14]. The most common methodologies for these types of measurements are the use of on-machine probing using touch-trigger probes, scanning probes, or to check the part with a gauge. The purpose of this type of inspection is to determine whether the manufactured product meets the design specified tolerances. On the other hand, reference artifacts with known dimensions are measured on the machine for machine calibration. The difference between the measured dimensions and the reference dimensions is used to assess the accuracy and manufacturability of that particular machine tool.

Post-process measurements are the traditional methods of part inspection and can be performed using a variety of instruments [4]. Post-process inspection is commonly used to scrutinize the quality of the products and to monitor the performance of the manufacturing processes [8, 9]. A common practice is to relate the results of post-process inspection to the quality of the finished workpiece and the performance of manufacturing equipment. Therefore, the inspection results are often used to control or fine tune the manufacturing process.

In summary, pre-process metrology can be used to insure that the manufacturing machines and measuring instrument and machines have the appropriate accuracy. Process-intermittent metrology can be used for process control and, if used properly, capture the signature of machine performance over time. Post-process metrology can be used to independently confirm the final product quality and certify the process performance. The system is interconnected and each portion performs a function that is both independent and interdependent. Proper attention to detail is required in all steps of the manufacturing process, from machine acceptance to final part inspection.

EXPERIMENTAL PROCEDURE

This study has been implemented in three phases. Phase I was conducted at Ford's Scientific Research Laboratory. Phase II was conducted at Sandia National Laboratories. Phase III is currently being conducted at Arizona State University. In the following section, details on experimental procedure, computational algorithm, and machine error correction are presented.

The specific goals of Phase I are: (1) determining the most appropriate on-machine probing technique and (2) using part dimensional data to diagnose machine tool errors. First, the experimental procedures and specifications were developed and documented. A laser interferometry system was used to evaluate the linear displacement accuracy of a machining center. The results show that the average linear displacement error is about ± 25 μm and displacement error caused by backlash is significant. For the cutting test, two modified NAS 979 standard test parts [13] were cut. The modified NAS 979 parts were used to evaluate the feasibility and capability of on-machine inspection with touch-trigger probing system. On-machine probing procedures for probe calibration, part datum setting, and part measurement were developed and documented. A post-process inspection program was also developed and both test parts were measured on a coordinate measuring machine. The results show that the average part dimensional error is about ± 35 μm in z axis and ± 40 μm in x and y axes. The results also show that the backlash effect can be observed by comparing the probed center location of various hole features.

The specific goal of Phase II is to develop sensor fusion methodology that enhances the capability of CNC machines for precision manufacturing. Laser interferometer and telescopic ball bar were used to evaluate the machine performance in linear displacement and contouring for a conventional machining center. Error models were derived for machine performance assessment and prediction. Cutting tests were conducted to assess machining capability. Derived error model was implemented on an open-architecture controller to compensate for the machine error.

A laser interferometer was used to calibrate the linear displacement accuracy of the vertical machining center. The range of the calibration is 20 inches in x axis, 16 inches in y axis, and 8 inches above a Kurt vise in z axis, respectively. The selected workspace was divided into a set of 4×4×4 cubic spaces. The grid points where the boundary corners of those cubic spaces overlap are the designed measurement points. The calibration data was collected along those boundary lines at every inch of displacement.

Linear regression analysis was used to obtain the best fitted polynomial function for each calibration data set.

$$f = a_0+\Sigma a_i x^i; \; i = 1, ..., n$$

While fitting those polynomial functions, the R square values, is a measure of the amount in the variability of predicted value obtained by using the regression model, were used to determine the quality of the fit. Where $0 \le R^2 \le 1.0$. In all cases, the R square values were within the range of 0.85 and 0.96, which can be interpreted as a high quality fit.

A computational algorithm was develop for machine inaccuracy estimation. By specifying the tool position in the machine coordinate system, the algorithm will first identify the grid space within which the tool is positioned. As the grid space was identified, the four corner points and their corresponding polynomial functions were determined. Weighting factors were determined based on the relative distance of the tool position and the four adjacent corner points as follows.

$$W_{xi} = |y - y_k||z - z_k| / |y_1 - y_4||z_1 - z_2|$$
$$W_{yi} = |x - x_k||z - z_k| / |x_1 - x_4||z_1 - z_2|$$
$$W_{zi} = |x - x_k||y - y_k| / |x_1 - x_4||y_1 - y_2|$$

where k = Mod(i + 2) and i = 1,2,3,4. The estimated displacement inaccuracy at the particular tool position was then determined as follows.

$$\Delta x = \Sigma w_{xi} f_{xi}(x);$$
$$\Delta y = \Sigma w_{yi} f_{yi}(y); \quad i = 1,2,3,4.$$
$$\Delta z = \Sigma w_{zi} f_{zi}(z);$$

To verify the effectiveness of the calibration and the interpolation accuracy of the derived computational model, the predicted values were compared with the laser interferometer readings at various points within the selected workspace. The results, Figure 1, show that the linear displacement inaccuracy of the vertical machining center could be predicted and compensated for with an average of 80% accuracy.

Cutting tests were conducted to assess the machine performance in producing parts. To study the machine performance at different locations within the workspace, two modified NAS 979 test parts, Figure 2, were produced. One test part was located at the right side of the worktable and the other one was located at the left side of the worktable. The same NC program, tooling, and cutting parameters were used for producing both parts.

The dimension of both test parts were measured using process-intermittent probing technique with a touch-trigger probe. The part coordinate systems (PCS) were established by probing the four edges, top surface, and a bored center hole of the test part. The determined center location of the bored center hole was used to set the origin of the PCS. The determined top surface was used to set the reference plane of the PCS. The best fit line along a particular edge was used to set the orientation of the PCS. The same process-intermittent probing routine was repeatedly conducted for 35 times to capture the machine performance variation over a range of temperature profiles. The temperature profile of the machine structure was changed by running various designed warm-up cycles.

The dimensions of both test parts were then measured on a coordinate measuring machine (CMM) in post-process inspection. To maintain a high level of data compatibility, the post-process inspection routine was designed to be extremely similar to that of the process-intermittent probing. The difference between the two measurement procedures was that the sample density of the post-process inspection was about twice that for process-intermittent probing. In this study, 19 repeated CMM measurements were conducted for each test part. The mean and the variance of each repeated feature measurement were calculated. Student's T-test was conducted to determined the statistical significance of the difference between two means from the repeated measurement of both test parts. The F-test was conducted to determine the statistical significance of the difference between two variances from the repeated measurement of both test parts. The results, Table 1 & 2, show that in most of the cases the mean and variance of the two repeated feature measurements were not significantly different. This could be interpreted as the machine performs consistently over the designated workspace.

In order to compare the measurement data for process-intermittent probing and post-process inspection, the same CMM fitting algorithm was used to obtain the geometric characteristics of various features such as dimension, circle diameter, circle center, roundness, circularity, flatness, straightness, squareness, parallelism, etc. Since a CMM has higher accuracy than a conventional machining center, the information obtained from CMM measurement could be used as the reference for machine performance assessment. A prior study shows that the difference between the CMM data and on-machine probing data could be used to identify and characterize machine related errors [10, 11].

The error model derived with laser interferometer calibration data was also used to estimate the dimensional inaccuracy of manufactured parts. The potential error at each probing point was predicted by using the error model. Therefore, for each probing point, three different types of data are available for direct comparison. By comparing the process-intermittent gauging data obtained from on-machine probing with the post-process inspection data obtained from CMM probing, the machine inaccuracies could be identified. By comparing the error model prediction with the difference between the process-intermittent gauging data and the post-process inspection data, the modeling inaccuracies could be identified. If the modeling inaccuracy is within the specified tolerance range for a particular product, the derived error model could be used for product quality assessment prior to actual production as well as for error correction that could lead to a reduction in manufacturing variation. The results, Table 3, show that the error model derived from laser calibration can be used to predict the part dimension variation with up to 85% accuracy. On the other hand, the on-machine probing results show a slightly larger discrepancy than CMM measurement and model prediction.

For error correction, an open-architecture control environment is essential [15]. Currently, several commercial controllers designed with an open-architecture platform are readily available. Therefore, the derived error assessment and reduction algorithm can be easily installed onto those open-architecture controllers to enhance the machine performance in manufacturing high quality parts. The vertical machining center located in the Integrated Manufacturing Technologies Laboratory at Sandia National Labs in Livermore, California is one of the machines that is equipped with an open-architecture controller. The derived error correction module was smoothly integrated with the developed control software. The error correction module reads the encoder signal to interpret the tool position in the machine coordinate system. The tool position is then fed to the computational algorithm to determine the machine inaccuracy at that position. The calculated position error value is combined with the original position signal to determine a new commanded position. The modified command signal is then converted back to encoder signal for position error correction. The results in Figure 1 show that the machine linear displacement error was significantly reduced.

CONCLUSIONS

The development of sensor fusion methodology advances the accuracy and capability of manufacturing and inspection processes. The methodology also provides a means for integrating more sensing and analysis capabilities at the machine level. Using sensor fusion techniques, methods could also be derived to extract information on the compound part quality variation resulting from machine, process, and fixture related errors. Therefore, their degradation effect can be decoupled and minimized.

The development of an adaptive error modeling system with sensor fusion technologies has facilitated the monitoring and controlling of manufacturing processes. The adaptive error modeling system is capable of receiving information from various sensors, assessing the status of the process, and determining the proper action. Therefore, the developed system enhances the capabilities of a machining center in making quality parts as well as assessing the conformity of workpiece dimensions to the imposed dimensional tolerances.

Currently, Phase III study is under way at Arizona State University. The effort is focused on the analysis and interpretation of the intrinsic correlation between the measurement data obtained from the laser interferometry system, on-machine probing, and post-process inspection.

ACKNOWLEDGMENT

This work was funded by the NSF GOALI program and cost shared by Sandia National Laboratories (DMI-9709390) and Ford Motor Company (DMI-9631830). The authors would like to express their gratitude to Dr. Gwo-Luh Lee, Jing Song, Charles Steinhaus, and Dr. Jon Baldwin for their technical support and participation in this study.

REFERENCES

1. ANSI/ASME B5.54-1992, 1992, Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers, ASME, New York.
2. Chen, J. S., Yuan, J. S., Ni, J., and Wu, S. M, 1993, "Real-time Compensation for Time-variant Volumetric Errors on a Machine Center," *ASME Transactions on Journal of Engineering for Industry*, Vol. 115, pp. 472-479.
3. Donmez, M.A., Blomquist, D.S., Hocken, R.J., Liu, C.R., and Barash, M.M., 1986, "A General Methodology for Machine Tool Accuracy Enhancement by Error Compensation," *Precision Engineering*, Vol. 8, No. 4, pp. 187-196.
4. Farago, F. T., 1982, Handbook of Dimensional Measurement, 2nd Ed., Industrial Press, Inc., New York.
5. Ferreira, P.M., and Liu, C.R., 1993, "A Method for Estimating and Compensating Quasistatic Errors of Machine Tools," *ASME Transactions on Journal of Engineering for Industry*, Vol. 115, pp. 149-159.
6. Hocken, R.J., Simpson, J.A., Borchardt, B., Lazar, J., Reeve, C., and Stein, P., 1977, "Three Dimensional Metrology," *CIRP*, Vol. 26, No. 1, pp. 403-408.
7. Hocken, R.J., 1991, "A New Standard for the Performance of Coordinate Measuring Machines," *Proceedings of the 1991 NSF Design and Manufacturing Systems Conference*, pp. 823-828.
8. Hocken, R.J., 1995, "Measurement Integration," in Coordinate Measuring Machines and Systems, edited by Bosch, J.A., Marcel Dekker, Inc., New York.
9. Menq, C.-H., Yau, H.-T., and Wang, C.-L., 1992, "An Intelligent Planning Environment for Automated Dimensional Inspection Using Coordinate Measuring Machines," *ASME Transactions on Journal of Engineering for Industry,* Vol. 112, Vol. 2, pp. 222-230.

10. Mou, J., Donmez, M.A., and Cetinkunt, S., 1995a, "An Adaptive Methodology Using Features-Based Analysis Techniques for Machine Performance Improvement: Part I - Theory Derivation," *ASME Transactions on Journal of Engineering for Industry*, Vol. 117, No. 4, pp. 584-590.
11. Mou, J., Donmez, M.A., and Cetinkunt, S., 1995b, "An Adaptive Methodology Using Features-Based Analysis Techniques for Machine Performance Improvement: Part II - Experimental Verification," *ASME Transactions on Journal of Engineering for Industry*, Vol. 117, No. 4, pp. 591-600.
12. Mou, J. and Liu, C.R., 1996, "An Innovative Approach to Increase the Accuracy of Multi-Axis Machines for Process-Intermittent Inspection," *ASME Transactions on Journal of Manufacturing Sciences and Engineering*, Vol. 118, No. 4, pp. 585-594.
13. National Aerospace Standard, 1969, "Uniform Cutting Tests - NAS Series Metal Cutting Equipment Specifications," Aerospace Industries Association of America Inc., Washington D. C..
14. Roe, J., 1986, "Probing for precision and Productivity," *Biennial International Machine Tool Technical Conference*, Vol. 12, pp. 173-180.
15. Wright, P., Schofield, S., and Wang F.-C., "Open Architecture Control For Machine Tools," *Proceedings of 13th Symposium on Engineering Applications of Mechanics: Manufacturing Science and Engineering of 1996 CSME Forum*, pp. 1-17.

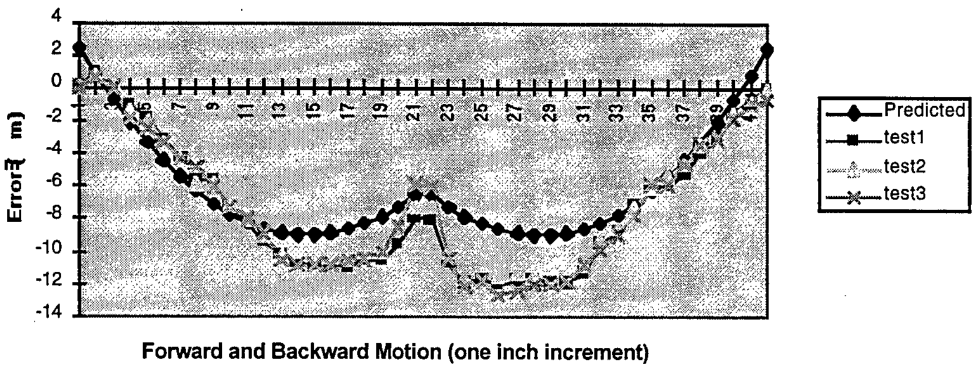

FIGURE 1 LINEAR DISPLACEMENT ERROR MEASUREMENT AND PREDICTION.

TABLE 1 T-TEST FOR ON-MACHINE PROBING MEAN COMPARISON.

	Mean 1	Mean 2	T-test
Bore Hole Diameter	1.50615	1.50596	0.08946
X Edge Dimension	3.00051	3.00021	0.00062
Y Edge Dimension	3.00042	3.00044	0.73211
Z Dimension	0.24921	0.24930	0.0
Circle Diameter	6.00071	6.00074	0.74922
Circle Center X	0.00014	0.0001	0.20109
Circle Center Y	0.00036	0.00023	0.00011
Hole Diameter	0.50139	0.50133	0.54124

TABLE 2 F-TEST FOR ON-MACHINE PROBING VARIANCE COMPARISON.

	Var 1	Var 2	F-test
Bore Hole Diameter	0.00031	0.00024	0.36779
X Edge Dimension	0.00019	0.00022	0.59628
Y Edge Dimension	0.00017	0.00016	0.72481
Z Dimension	2.67E-05	0.0	0.0
Circle Diameter	0.00026	0.00020	0.36637
Circle Center X	8.52E-05	8.77E-05	0.91713
Circle Center Y	7.45E-05	8.25E-05	0.71697
Hole Diameter	0.00028	0.00020	0.21220

TABLE 3 DATA COMPARISON FOR SENSOR FUSION.

	CMM Probing	On-machine Probing	Laser Prediction
Bore Hole Diameter	1.5061	1.5120	1.5000
X Edge Dimension	3.0005	2.9977	2.9999
Y Edge Dimension	3.0002	2.9971	3.0001
Z Dimension	0.2492	0.2491	0.2500
Circle Diameter	6.0007	5.9941	6.0000
Circle Center X	0.0001	0.0004	0.0001
Circle Center Y	0.0004	0.0008	0.0002
Hole Diameter	0.5014	0.5019	0.5009

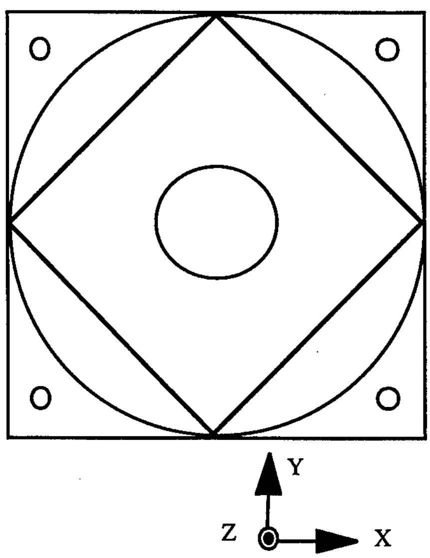

FIGURE 2 MODIFIED NAS979 TEST PART.

Report Number (14) SAND--98-8499C

CONF-980548--

Publ. Date (11) 199803

Sponsor Code (18) DOE/ER, XF

UC Category (19) UC-406, DOE/ER

DOE