MACHINE PERFORMANCE ASSESSMENT AND ENHANCEMENT FOR A HEXAPOD MACHINE

SAND--98-8501C
CONF-980539--

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

RECEIVED
MAR 27 1998
OSTI

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

KEYWORDS

Machine performance enhancement, Error modeling, Error compensation.

ABSTRACT

The focus of this study is to develop a sensor fused process modeling and control methodology to model, assess, and then enhance the performance of a hexapod machine for precision product realization. Deterministic modeling technique was used to derive models for machine performance assessment and enhancement. Sensor fusion methodology was adopted to identify the parameters of the derived models. Empirical models and computational algorithms were also derived and implemented to model, assess, and then enhance the machine performance. The developed sensor fusion algorithms can be 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 hexapod machine's capability to produce workpieces within the imposed dimensional tolerances.

INTRODUCTION

Traditional industrial robots are open-chain mechanisms constructed of consecutive links connected by rotational or prismatic joints with one degree of freedom. They exhibit low stiffness and poor positioning accuracy, therefore, are not suitable for large loads and high accuracy applications [2,10]. On the other hand, compared with serial manipulator, parallel structured robots and machines have the advantages of (1) high force/torque capacity since the load is distributed to several in-parallel actuators, (2) high structural rigidity, and (3) better accuracy due to non cumulative joint error. Hence, in recent years an increasing number of researches have been focused on the parallel mechanism, mainly for the attractive performances they can offer in the robotic and manufacturing application [3,6].

Since proposed by Stewart in 1965 [1], parallel structured platform and manipulator have been used in many applications such as aircraft simulators and robot wrist. The hexapod machine is one of the recent developments based on the Stewart platform concept. Despite the aforementioned advantages over serial structured machines and the recent technology advancement in designing and controlling of parallel structured machines [4,5,7,8,9,12], the performance of parallel structured machine tools will be degraded due to the imperfections at manufacturing and assembly stages. Hence, there is a need to develop robust and effective method for hexapod machine performance assessment and enhancement.

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.

The focus of this study was to develop a sensor fusion methodology 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 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.

19980504 096

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

DTIC QUALITY INSPECTED 4

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The developed sensor fusion algorithms can be 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. Since more accurate and on-time product monitoring and control are achieved, the methodology is capable of enhancing machine performance, improving part-to-part repeatability, increasing flexibility, reducing cycle time, and increasing the accuracy of the machined features. This will enhance a hexapod machine's capability to produce workpieces within the imposed dimensional tolerances.

In this paper, an error compensation algorithm is proposed to use inverse kinematic model and regression analysis method to model and enhance the accuracy performance of a hexapod machine located within the Sandia National Labs in Livermore, California. Both 1-D and 5-D laser interferometer systems were used to calibrate the hexapod machine. Regression analysis technique was used to analyze the collected data and construct the polynomial functions for machine error modeling. Performance assessment algorithm was developed to predict the linear displacement errors of any point within designated machine workspace. The predicted error information was then translated into six struts' length error by using an inverse kinematic model. With the support of open-architecture control environment, strut length errors can be fed back to the controller to compensate for the displacement errors and thus improve the machine's accuracy in real-time.

INVERSE KINEMATIC MODEL

The configuration of a parallel structured hexapod machine that has six identical struts is shown in Fig 1. The lower platform, called the "BASE", is a semi-regular hexagon. The upper platform, which is referred to as the "TOP", is an equilateral triangle. One end of each strut is connected to the vertices of the base platform through a three-degree of freedom universal joints. The other end of a strut is connected to another strut through a bifurcated joint first to form a pair-linked structure. Each pair-linked structure is then connected to the vertices of the top platform through a three-degree of freedom universal joints. The whole system has six degrees of freedom. The BASE frame is established by fixing the reference coordinate system (X, Y, Z) at the center of the base platform with the Z-axis pointing vertically upward. The TOP frame is established by fixing the tool coordinate system (x, y, z) at the center of gravity of the top platform with the z-axis normal to the platform and pointing outward.

Let's define the lengths of the six struts as L_1, L_2, L_3, L_4, L_5, and L_6. Denote the location of the origin of the TOP frame with respect to the BASE frame by $[P_x, P_y, P_z]$. Let (α, β, γ) represent the rotation angles defined by rotating the TOP frame first about the X-axis with α degrees, then about the Y-axis with β degrees, and finally about the z-axis with γ degree. The rotation angles α and β are used to define an "approach vector" of the upper platform while γ is used to define the roll angle about the approach vector.

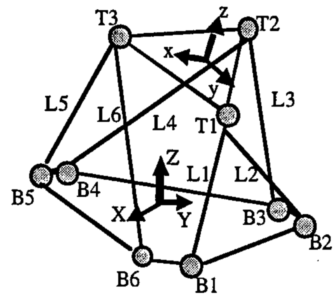


FIGURE 1 HEXAPOD MACHINE CONFIGURATION.

According to the Euler angle, the transformation matrix between the mobile TOP frame and the fixed BASE frame can be derived as follows.

$$T_{BASE}^{TOP} = \begin{bmatrix} C\beta C\gamma + S\alpha S\beta S\gamma & -C\beta S\gamma + S\alpha S\beta C\gamma & C\alpha S\beta & P_x \\ C\alpha S\gamma & C\alpha C\gamma & -S\alpha & P_y \\ -S\beta C\gamma + S\alpha C\beta S\gamma & S\beta S\gamma + S\alpha C\beta C\gamma & C\alpha C\beta & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where C denotes cos. and S denotes sin.

The coordinates of the TOP frame's vertices can be transformed to the BASE coordinate system through the transformation matrix as follows.

$$\begin{bmatrix} X_{T_i} \\ Y_{T_i} \\ Z_{T_i} \\ 1 \end{bmatrix} = T_{BASE}^{TOP}(P_x, P_y, P_z, \alpha, \beta, \gamma) \begin{bmatrix} x_{T_i} \\ y_{T_i} \\ z_{T_i} \\ 1 \end{bmatrix}$$

Thus the six struts length can then be determined as

$$L_i = \left| \left(\bar{X}_{B_i}, \bar{Y}_{B_i}, \bar{Z}_{B_i}\right) - \left(\bar{X}_{T_i}, \bar{Y}_{T_i}, \bar{Z}_{T_i}\right) \right|; \quad i = 1,2,\ldots,6.$$

ERROR ASSESSMENT AND REDUCTION

The error assessment and compensation is based on the data collected with both 1-D and 5-D laser interferometer systems. The 1-D laser system was used to measure the linear displacement accuracy of the machine. The 5-D laser system was used to measure the linear displacement accuracy, angular accuracy (pitch and yaw), and two straightness accuracy per each calibration measurement. The range of the calibration is 16 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. A general form for best-fitted polynomial of x-axis measurement can be expressed as follows.

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

While fitting those polynomial functions, the R square values were used to determine the quality of the fit. In all cases, the R square values were within the range of 0.95 and 0.99, which can be interpreted as a high quality fit.

A computational algorithm was developed 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 shown in Figure 2.

$$W_{xi} = |Py - Py_k||Pz - Pz_k| \,/\, |Py_1 - Py_4||Pz_1 - Pz_2|$$

$$W_{yi} = |Px - Px_k||Pz - Pz_k| \,/\, |Px_1 - Px_4||Pz_1 - Pz_2|$$

$$W_{zi} = |Px - Px_k||Py - Py_k| \,/\, |Px_1 - Px_4||Py_1 - Py_2|$$

where k = Mod(i + 2) and i = 1,2,3,4.

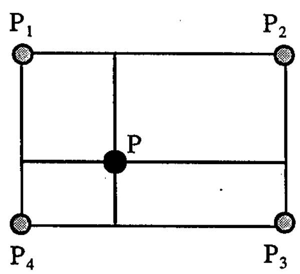


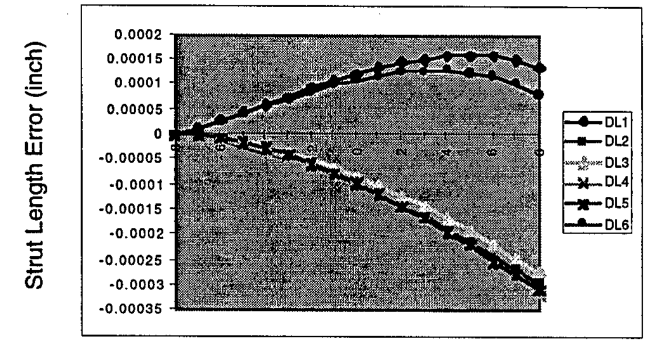
FIGURE 2 WEIGHTING FACTOR DETERMINATION SCHEME.

The estimated displacement inaccuracy at the particular tool position was then determined as follows.

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

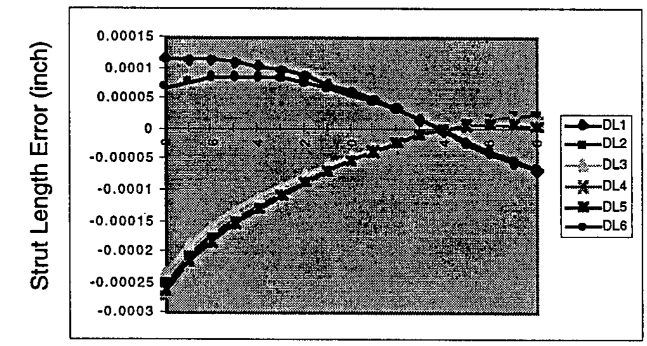
The same method can be extended to the backward displacement error estimation.

Using the inverse kinematic model, the ideal strut length and actual strut length can be calculated. The difference between the ideal and actual strut length is defined as strut length error and expressed as $\Delta L = L_{actual} - L_{ideal}$. The results show that the strut length error, as shown in Figure 3, can be determined for both forward and backward displacements based on the linear displacement error data collected from using 1-D laser interferometer system.



1-D Laser Interferferometer Data Analysis

(a) Forward (X: -8 → +8)

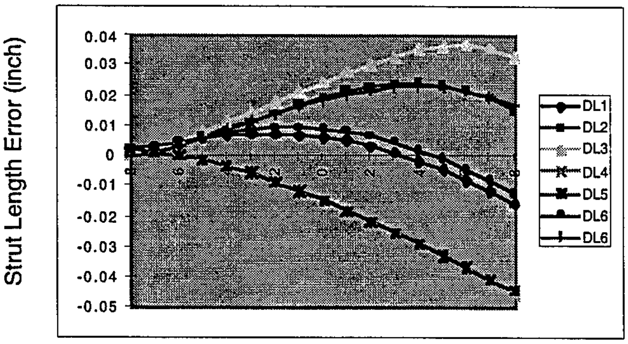


1-D Laser Interferferometer Data Analysis

(b) Backward (X: -8 ← +8)

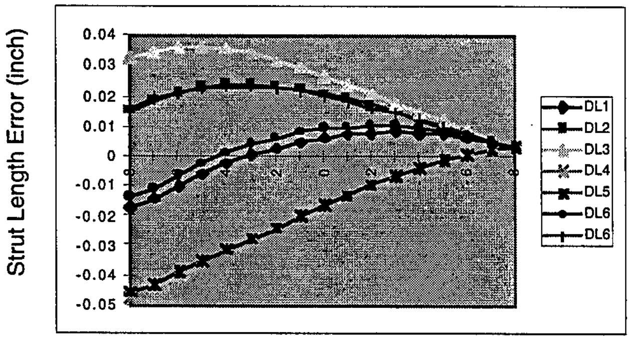
FIGURE 3 CALCULATED STRUT LENGTH ERROR WITH 1-D LASER INTERFEROMETER MEASUREMENT.

A 5-D laser interferometer was also used to calibrate and evaluate the machine performance in linear displacement, angular accuracy (pitch and yaw), and straightness. Same inverse kinematic model was used for machine performance assessment, prediction, and enhancement. The results show that the strut length error can be determined for both forward and backward displacements based on the data of linear displacement error, angular errors (pitch and yaw), and straightness errors collected from using 5-D laser interferometer system, as shown in Figure 4.



5-D Laser Interferferometer Data Analysis

(a) Forward (X: -8 → +8)



5-D Laser Interferferometer Data Analysis

(b) Backward (X: -8 ← +8)

FIGURE 4 CALCULATED STRUT LENGTH ERROR WITH 5-D LASER INTERFEROMETER MEASUREMENT.

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 show that the linear displacement inaccuracy of the vertical machining center could be predicted and compensated for with an average of 70% accuracy.

For error correction, an open-architecture control environment is essential [11]. Currently, several commercial controllers designed with an open-architecture platform are readily available. Therefore, the derived error assessment and reduction algorithm, as shown in Figure 5, can be easily installed onto those open-architecture controllers to enhance the machine performance in manufacturing high quality parts.

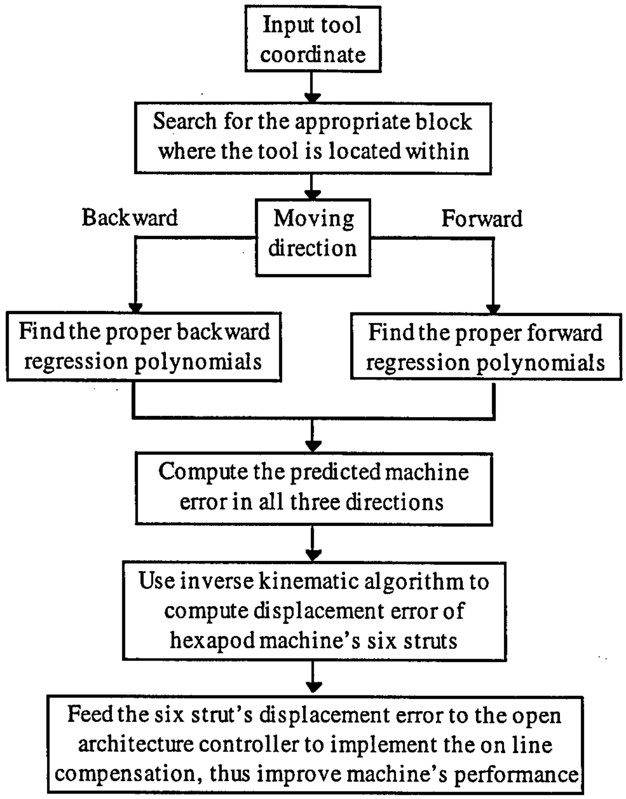


FIGURE 5 ERROR PREDICTION AND COMPENSATION FLOWCHART.

CONCLUSIONS

Inverse kinematic model and error compensation algorithm for hexapod machine performance assessment and enhancement are presented. Linear regression technique was used to analysis data collected from both 1-D and 5-D laser interferometer systems and to construct the polynomial functions for machine error assessment. Since the error compensation model is based on the collected data, the reliability and repeatability of the data collection should be guaranteed. The same point can be measured several times, and the average value can be utilized to derive the model. At the same time, the measuring surrounding's temperature and humidity should also be taken into consideration since these factors have affluence on the performance of the hexapod machine.

The aim of this research is to find the six struts' displacement errors for machine performance enhancement. The developed error compensation algorithm could be embedded on an open-architecture controller to perform the real- time machine performance enhancement. According to the actual testing, the performance of hexapod machine can be improved by 70% without any significant cost on hardware enhancement. By incorporating the temperature and humidity factors into the error compensation model, the developed error correction module can be further improved.

The development of sensor fusion methodology provides a means for integrating more sensing and analysis capabilities at the machine level. Therefore, the machine performance enhancement system could advance the accuracy and capability of a hexapod machine in making quality parts.

REFERENCE

1. Stewart, D., (1965), "A Platform with Six Degrees of Freedom," *Proc. Instn. Mech. Engrs.*, 180, No. 15, pp. 371-386.
2. El-Khasawneh, B. S. and P. M. Ferreira, (1997), "On Using Parallel Link Manipulators as Machine Tools," *Transaction of NAMRI/SME,* Volume XXV, pp. 305-310.
3. Griffis, M. and J. Duffy, (1989), "A Forward Displacement Analysis of a Class of Stewart Platforms," *Journal of Robotic Systems*, Vol. 6, No. 6, pp. 703-720.
4. Innocenti, C. and V. Parenti-Castelli, (1990), "Direct Position Analysis of the Stewart Platform Mechanism," *Mechanical Machine Theory*, Vol. 25, No. 6, pp. 611-621.
5. Liu, K., J. M. Fitzgerald, and F. L. Lewis, (1993), "Kinematic Analysis of a Stewart Platform Manipulator," *IEEE transaction on Industrial Electronics*, Vol. 40, No. 2, pp. 282-293.
6. Merlet, J-P., (1992), "Direct Kinematics and Assembly Modes of Parallel Manipulators," *The International Journal of Robotics Research*, Vol. 11, No. 2, pp. 150-162.
7. Notash, L. and R. P. Podhorodeski, (1996), "Forward Displacement Analysis and Uncertainty Configurations of Parallel manipulations with a Redundant Branch," *Journal of Robotic System*, Vol. 13, No. 9, pp. 587-60.
8. Pang, H. and M. Shahinpoor, (1993), "Analysis of Static Equilibrium of a Parallel Manipulator," *Robotica*, Vol. 11, pp. 433-443.
9. Tajbakhsh, H. and P. M. Ferreira, (1997), "Kinematic Error Estimation and Transmission Error Bounding for Stewart Platform Based Machine Tools," *Transaction of NAMRI/SME,* Volume XXV, pp. 323-328.
10. Wang, J. and O. Masory, (1993), "On the Accuracy of a Stewart Platform - PART I, The Effect of Manufacturing Tolerances," *Proceedings of IEEE International Conference Robotics and Automation*, pp. 114-120.
11. Wright, P., Schofield, S., and Wang F.-C., (1996), "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.
12. Zhuang, H. and Z. S. Roth, (1993), "Method for Kinematic Calibration of Stewart Platforms" *Journal of Robotic System*, Vol. 10, No. 3, pp. 391-405.

M98052522

Report Number (14) SAND--98-8501C

CONF-980539--

Publ. Date (11) 19980319

Sponsor Code (18) DOE/ER, XF

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

DOE