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Reconfigurable data driven virtual machine tool: Geometric error modeling and evaluation

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ABSTRACT

Standards communities are developing robust machining and instrumented performance tests to evaluate the accuracy of 5-axis machining centers through the direct and indirect measurement of errors affecting the simultaneous motion of all five axes. The combined effect of the numerous geometric errors and servo errors complicates diagnostic analysis of the measurement results and estimation of the individual errors. To better understand the effect of the individual errors on the measurement results, we developed a reconfigurable five-axis data driven virtual machine tool (DDVMT) error simulator. The DDVMT is a generalized model that incorporates machine tool information models, geometric error models, controller models, and (standardized) machine tool metrology test methods and analyses into one modeling scheme. This paper describes the data driven virtual machine tool and demonstrates its ability to simulate the effects of geometric errors on multi-axis performance tests.

Introduction

Five-axis machine tools[2] provide manufacturers with the capability to efficiently manufacture complex parts. With two rotary and three linear axes, the orientation of the cutting tool can be optimally adjusted with respect to the workpiece. Thus, complex parts and surfaces can be efficiently manufactured with minimal setups and fixtures.

Five-axis machine tools have many errors that affect the realized tool path and thus workpiece geometry. These errors can be categorized as thermal errors, errors due to static and dynamic machine compliance, controller errors such as servo mismatch, and geometric errors. Each of these categories can have many contributing errors. As an example, five-axis machine tools can have at least 41 geometric errors, including offsets in the position of the axis average line of rotary axes, errors in the average relative alignment of axis motions, and angular and linear deviations in the motion of each axis. Machine tool errors vary between different machine configurations, manufacturers, models, and even machines of the same model. Furthermore, errors may change over time due to wear, crashes, and mishandling.

In an agile environment, knowledge of machine tool errors is essential for estimating machine capabilities, error compensation, reducing scrap and rework, and ensuring first part correct manufacturing. National and international standards [1–3] provide procedures for the direct measurement of each individual error. However, application of these procedures to characterize all the errors of 5-axis machine tools can be challenging and time consuming. Periodic checks of machines to ensure optimum performance can benefit manufacturers, but the machine downtime necessary to directly measure the errors can be cost prohibitive. To mitigate this problem, users are employing test procedures designed to measure the simultaneous effects of many errors [4–6] to quickly gage the overall performance of their machines.

Selecting the appropriate combination of axis motions and instruments necessary to determine the performance of a machine is challenging. Standards committees have recognized this challenge and are developing standard test methods for evaluating the performance of 5-axis machining centers through direct and indirect measurements of toolpath errors during the simultaneous motion of multiple axes [7,8]. However, the combined effect of errors of multiple axes complicates the diagnostic analysis of the

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measured data and the estimation of the individual errors. To better understand the effect of the individual geometric and servo control errors on the measurement results for various machines, we developed a data driven virtual machine tool (DDVMT) error simulator [9].

This paper describes the methodology for the DDVMT. A brief survey of machine tool error modeling is provided in second section. Machine tool standards and machine tool information models are briefly discussed in third section. A detailed description of the data driven modeling approach applied to geometric error modeling is provided in fourth section. Core features and modeling modules of the DDVMT are described in fifth section. Results of multi-axis simulations and measurements are provided in sixth section. Discussion of results and closing remarks are provided in last two sections.

Generalized machine tool error modeling

Machine tool error modeling is not a new concept. Many models have been developed to investigate the effects of machine tools' geometric errors, static and dynamic compliance, thermal behavior, and servo characteristics on workpiece geometry [10–13]. These models have also been used for the evaluation of test methods, for the evaluation of machine configurations, and for tool path error compensation [12–18]. Furthermore, information models [19] have been developed to facilitate the collection, archiving, use, and exchange of unambiguous machine tool data.

Machine tool error modeling is challenging due to the large variety in machine tool classes, configurations, accuracy levels, error sources, and applications. A recent publication suggests that machine tool error modeling is type and topology dependent and that no generic approach for modeling all machine tools exists [16]. We believe that a modular, data driven, modeling approach combining machine tool information models with existing error modeling schemes (e.g., geometric error modeling using homogeneous transformation matrices) is a significant step toward a robust generalized error modeling method. The generalized DDVMT presented in this paper applies information defined in machine tool information models to build error models for a variety of machine configurations using generic, modular, models for geometric errors and servo errors. We believe this is the first demonstration of combining the two model types into one generalized modeling method. The methodology can be extended to include (existing) models for other machine tool errors, such as compliance and thermal errors.

Machine tool standards and information models

Machine tool standards provide a common infrastructure that improves communication, efficiency, innovation, and interoperability through the standardization of terminology, measurement methods, analyses, and data formats [1,2,7,8,19,20]. Modeling platforms that conform to machine tool standards ensure compatibility between users, machines, and software and minimize modeling errors due to misinterpretation. The DDVMT is designed to be fully compatible with these standards by following their protocols, such as the identification [20] and orientation of coordinate systems [19], the designation for the configuration of machine axes [1,7], the location of measurement functional points [2,19], and the formats for both machine [19] and measurement data [21].

Machine tool information data files [19] are the core feature of the DDVMT, enabling the ability to automatically model multiple configurations and multiple machines. These files are generated following ASME B5.59-2, which defines electronic data formats for properties of machine tools, including machine tool performance data. Each file contains many data elements (see Example A.1 in Appendix) that describe the machine properties in a systematic structure. Examples of the types of elements defined in [19] and used by the DDVMT include the machine's identification (<DeviceID>), configuration (<MachineConfiguration>), work zone (<WorkZone>), axis properties (<Axes>), overall machine performance (<Performance>), and detailed error data (<MachineErrors>). Example 1 demonstrates the format (elements and sub-elements) used for representing the mean unidirectional positional deviation of the *X*-axis, e_{XX}, for a positive approach direction.

Example 1. XML sample describing the positioning errors of the *X*-axis, e_{XX}.


```
<MachineErrors>
<!- - The following is a sample of the <MachineErrors> element for a
machine tool. Many elements have been removed for simplicity. -->
  <Geometry>
    <AxisGeometry>
      <AxisName>X</AxisName>
      <MachinePosition>
        <AxisPosition>
          <AxisName>X</AxisName><Position>0</Position>
        </AxisPosition>
        <AxisPosition>
          <AxisName>Y</AxisName><Position>0</Position>
        </AxisPosition>
        <AxisPosition>
          <AxisName>Z</AxisName><Position>0</Position>
        </AxisPosition>
      </MachinePosition>
        <MeasurementOffset><Z>-200</Z></MeasurementOffset>
      <ErrorTable>
        <Measurand>X</Measurand>
        <Targets>0.00 -10.00 -20.00. . . </Targets>
        <ErrorData>
          <ApproachDirection>POSITIVE</ApproachDirection>
          <Values>-0.029 -0.027 -0.026 . . . </Values>
        </ErrorData>
      </ErrorTable>
    </AxisGeometry>
  </Geometry>
</MachineErrors>
```


The data defined in the information model is transferred to the DDVMT using the eXtensible Markup Language (XML) [22] where the pertinent data needed for a simulation is loaded into the generalized models. The data is expressed using a standard set of units, specified by ASME B5.59 Parts 1 and 2, to minimize errors in data exchange and to realize a fully generalized virtual machine tool. Any machine tool properly described in its information file can be modeled within seconds using the platform described here.

Data driven geometric error modeling

Geometric error modeling of a machine tool is normally achieved by building a kinematic model of the machine using homogeneous transformation matrices (HTMs) [13] that describe the rigid body kinematics of the machine tool as a function of axis positions and geometric errors. The model yields the errors in the position and orientation of the tool relative to the workpiece for each tool position of a machining or measurement process.

Kinematic models are generated by first dividing the structural loop of the machine tool into two series of machine elements (e.g., base *b*, positioning axes *A*, *B*, *C*, *X*, *Y*, and *Z*, spindle (*C*), workpiece *w*, and tool *t*) that represent the serial kinematic paths from the machine base to the workpiece and the path from the base to the tool. Coordinate frames are then attached to each machine element