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P.O. Box 10826, Raleigh, NC 27605-0826
(919) 839-8444 | Fax (919) 839-8039

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ASPE – The American Society for Precision Engineering
301 Glenwood Avenue, Suite 205, Raleigh, NC 27603
P.O. Box 10826, Raleigh, NC 27605
Telephone: (919) 839-8444 Fax (919) 839-8039
http://www.aspe.net

Preface

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A VIRTUAL MACHINE TOOL FOR THE EVALUATION OF STANDARDIZED 5-AXIS PERFORMANCE TESTS

Ronnie R. Fesperman, Shawn P. Moylan, and M. Alkan Donmez
Intelligent Systems Division
National Institute of Standards and Technology (NIST)
Gaithersburg, MD

INTRODUCTION

Standards committees are developing standard test methods for the performance evaluation of 5-axis machining centers through the direct and indirect measurement of simultaneous motions of all five axes [1-2]. However, the compound effect of the geometric and servo control errors of all axes complicates the analysis of the measured data and the identification and separation of the individual error contributor(s). To better understand the effect of the individual errors on the measurement results, NIST is developing a multi-configuration five-axis Virtual Machine Tool (VMT) model.

BACKGROUND

Machine tool error modeling is not a new concept. Many models have been developed to investigate the effects of machine tools' geometric errors, stiffness, thermal behavior, and servo characteristics on workpiece geometry [3-6]. These models have also been used for the evaluation of measurement methods, for the evaluation of machine topologies, and for tool path compensation [5-8]. Research has shown that geometric errors are dominant at low speeds and servo errors are more dominant at higher speeds [9]. This paper presents the design of a generic virtual machine tool software platform that combines both geometric errors and servo errors for a variety of machine configurations.

VIRTUAL MACHINE TOOL

Developed using commercially available numerical computation software, the VMT is designed to be a generalized versatile model that can be used to simulate and analyze the combined or independent effect of the individual geometric and servo errors on standard 5-axis performance test results [1]. Simulations of machining tests [2,10] and multi-axis kinematic tests [11] can be performed for many 5-axis machine tool configurations. In addition, the VMT may be used to predict the errors of workpieces machined by these types of machines.

The VMT is a software application that is the combination of six generalized computational modules (see Fig. 1). These are ideal trajectory generation (ITG), tool path animation (TPA), control error modeling (CEM), geometric error modeling (GEM), machine to workpiece coordinate system transformation (CST), and workpiece feature analysis (WFA). Versatility is achieved by populating the parameters of the generalized models with data described by machine specific information models [11] transferred using the e**X**tensible **M**arkup **L**anguage (XML) [13].

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 [1,2,12,14-16]. The VMT is designed to be fully compatible with these standards by following their protocols, such as the identification and orientation of coordinate systems, the designation for the configuration of machine axes, the location of measurement functional points, and the formats for both machine and measurement data.

Machine tool information files are the core feature of the VMT, providing the ability to 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 the machine tool performance data (e.g., linear positioning errors) [12]. Each file is machine

 The full descriptions of the procedures used in the paper require the identification of certain commercial products and their suppliers. The inclusion of such information should in no way be construed as indicating that such products or suppliers are endorsed by NIST or are recommended by NIST or that they are necessarily the best materials, instruments, software or suppliers for the purposes described.

specific and contains many data elements that describe the machine properties in a systematic structure. Examples of the types of elements defined in [12] include the machine's identification (ID), configuration, work zone, axis properties, performance, and errors. A short example of how data is stored is provided below as Example 1. This example demonstrates the format used for representing the mean unidirectional positional deviation of the X-axis for a positive approach direction.

EXAMPLE 1. X-axis linear positioning error, E_{XX}.

```
<MACHINE_ERRORS>
  <GEOMETRY>
    <AXIS_GEOMETRY>
        <AXIS_NAME>X</AXIS_NAME>
      <ERROR_TABLE>
        <MEASURAND>X</MEASURAND>
        <TARGETS>0.00 -10.00 -20.00. . . </TARGETS>
      <ERROR_DATA>
      <APPROACH_DIRECTION>POSITIVE</APPROACH
      _DIRECTION>
        <VALUES>0.00 -0.027 -0.020 . . . </VALUES>
      </ERROR_DATA>
        </ERROR_TABLE>
      </AXIS_GEOMETRY>
    </GEOMETRY>
</MACHINE_ERRORS>
```

The VMT is driven by simulation data files based on a general format similar to ASME B5.59 and written using XML. These files contain information used to identify the machine under evaluation, the workpiece, the workpiece location and orientation, the tool, the tool position relative to the workpiece (numerical control program), and simulation and analysis selection parameters. The parameters provide information pertaining to the analysis to be performed on the results, simulation speed, and Boolean type parameters used to activate and deactivate the various sources of machine error, e.g., servo control and geometric errors. The information pertaining to the machine, workpiece, and cutting tool are used as pointers for automatically acquiring data files and algorithms from various data repositories affiliated with the VMT. A short example of how errors are selected using "ON" and "OFF" statements is provided as Example 2. In Example 2, the linear positioning error for the X-axis, E_{XX}, is activated and the straightness error of the X-axis in the Y-direction, E_{YX}, is deactivated.

EXAMPLE 2. Error Selection Elements.

```
<ERROR_SELECTION>
  <GEOMETRY>
   <AXIS_ERRORS>
     <AXIS>
      <AXIS_NAME>X</AXIS_NAME>
      <ERROR_SELECTION>
        <MEASURAND>X</MEASURAND>
        <VALUE>ON </VALUE>
      </ERROR_SELECTION>
      <ERROR_SELECTION>
        <MEASURAND>Y</MEASURAND>
        <VALUE>OFF </VALUE>
      </ERROR_SELECTION>
     </AXIS>
   </AXIS_ERRORS>
  </GEOMETRY>
</ERROR_SELECTION>
```

The computational modules of the VMT are described below.

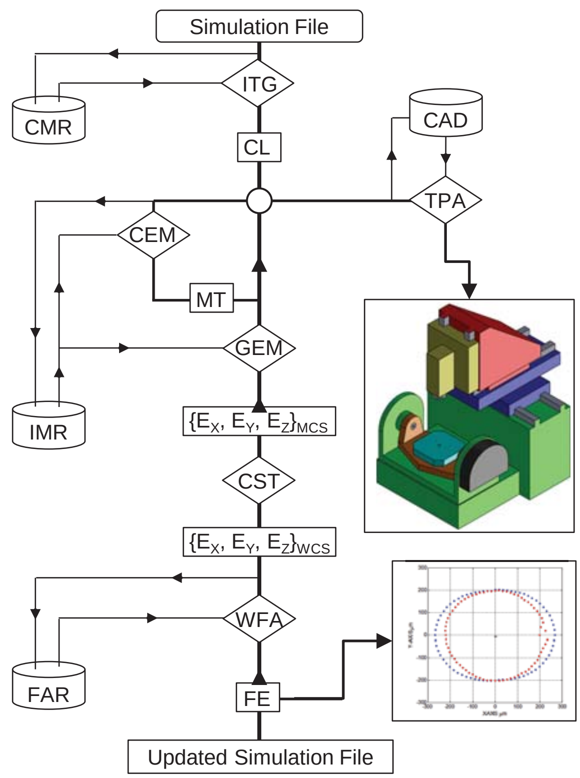

FIGURE 1. VMT Schematic

Ideal Trajectory Generation (ITG)

The numerical control (NC) program describes the cutting tool's nominal motion relative to the workpiece. The machine controller interpolates between the programmed points for each axis and moves the cutting tool and the workpiece along a smooth trajectory. Similarly, the VMT has a trajectory generation module with the capability of selecting a suitable trajectory generation method from the control model repository (CMR). An example of the type of method used by the VMT is jerk limited feedrate modulation [17]. The ideal trajectory generation module uses the selected method to generate the cutter location (CL) data, which describes the position of each axis as a function of time along an ideal trajectory.

Tool Path Animation (TPA)

To qualitatively verify the tool path, the CL data is processed by the tool path animator. In this module, pointers identifying the machine tool (manufacturer & model number) are used to retrieve the appropriate three-dimensional (3D) computer-aided design (CAD) models representing the machine tool components from the CAD repository. The CAD models are stored using the **ST**ereo**L**ithography (STL) file format and include models of the machine base and positioning axes. Once the models are retrieved, they are continuously printed to the screen and updated for each CL position using homogeneous transformation matrices (HTMs). The result is a 3D animation of the machine axes traversing along the prescribed tool path.

Control Error Modeling (CEM)

In this module, the ideal trajectory is modified to account for the effects of the machine tool servo characteristics and machine dynamics. This may include, but is not limited to, the effects due to mass, damping, friction, filters, and electrical gains. These effects can be simulated for each machine axis in the VMT's control error module, which uses general control schemes assembled using building blocks provided by the dynamic systems simulation software Simulink®. An example of such a control scheme is a nested closed-loop control of the drive motor current controller, velocity controller, and position controller. Information specifying the machine tool's serial number is used to retrieve machine specific control parameters (e.g., mass, damping, gains, and control scheme) from the machine information model repository (IMR). The data elements used for specifying these parameters are not described by ASME B5.59, but were added to the information model to support the VMT. This data is used to select, populate, and run the appropriate Simulink® block(s). The output of this module is a modified trajectory (MT) that includes the errors due to the control parameters.

Geometric Error Modeling (GEM)

The trajectory is also modified for the effects of the geometric errors of the machine tool. This is achieved by implementing a generalized geometric error modeling approach using homogeneous transformation matrices (HTMs) [6]. HTMs describing the rigid body kinematics of the machine tool are populated by interpolated error data associated with the particular machine tool being evaluated. The kinematic structure (order of the HTMs) of the machine is automatically constructed to provide the capability to model machines of different configurations. This is achieved by using the standard structural designation [1]. Consider the schematic of the machine shown in Figure 2. The standard designation for this configuration is [w'C'A'bXYZ(C)t], which identifies the kinematic chain from the workpiece to the base [wC'A'b] and from the base to the tool [bXYZ(C)t].

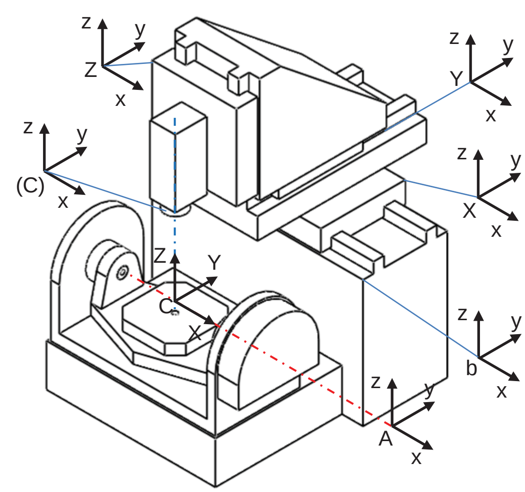

FIGURE2. Machine Configuration wC'A'bXYZ(C)t.

Characterizing the geometric errors of a machine tool normally involves measuring errors in the position and orientation of the tool relative to the workpiece at lines through functional points [15] within the machine work volume. Because of angular errors, measured positioning and straightness error values change as the functional point changes. Therefore, simulations of the geometric errors require knowledge of the measurement directions and locations of functional points used during the measurements, which are contained in the error data files. Furthermore, when measuring the relationship between two axes (e.g., squareness & parallelism) one has to select one of these axes as the reference axis (primary axis). This information is also contained in the error data files. The geometric error module (GEM) uses such metadata to define the axes coordinate systems and to calculate the relative movements between each. To simplify geometric error modeling, the current version of the VMT supports only data files containing error data in which all measurements were made through one functional point. This method places all machine coordinate frames at the same location in the machine work volume. The effects of all angular errors are calculated from the same zero position to minimize the uncertainties associated with coordinate frame offsets. The output from the GEM is a tool path error file that contains the components (E_X, E_Y, and E_Z) of the error vectors between the tool and workpiece corresponding to the nominal positions along the tool path.

Coordinate System Transformation (CST)

The error data generated by the GEM is in machine coordinates (MCS). This data must be transformed to workpiece (instrument) coordinates (WCS) to analyze the effect of the machine errors on the workpiece geometry (measurement). This is accomplished in the VMT's coordinate system transformation module. Information describing the machine's configuration is used to transform the trajectory error data to workpiece (instrument) coordinates. The output from this module is a workpiece data file that contains the data used to describe the nominal tool path in workpiece coordinates and the workpiece errors, $\{E_X, E_Y, \text{and } E_Z\}_{WCS}$, created by the machine tool.

Workpiece Feature Analysis (WFA)

Data from the workpiece error file is analyzed using algorithms from the feature analysis repository (FAR). These algorithms transform the workpiece error data to workpiece geometry or performance test parameters. The algorithms may include fitting circles, cylinders, and planes to the resulting data. The results from the analysis are then added to the simulation data file where it can be used by other software applications for future evaluation.

FINAL REMARKS

We provided a general description of a data driven virtual machine tool error model capable of simulating 5-axis performance test. Our VMT uses existing standards for test methods for machine tool performance as well as standards for representing machine data. Future work will involve modeling and simulating multiple machine tool configurations, testing and evaluating 5-axis performance tests, and integrating the system with a commercially available computer aided manufacturing (CAM) software package. In addition, the model will be developed to support information models containing error data measured through multiple functional points within the machine work volume.

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