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Single setup estimation of a five-axis machine tool eight link errors by programmed end point constraint and on the fly measurement with Capball sensor

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ABSTRACT

Five-axis machine tools can be programmed to keep a constant nominal tool end point position while exercising all five axes simultaneously. This kinematic capability allows the use of a 3D proximity sensing head mounted at the spindle to track the position changes of a precision steel ball mounted on the machine table effectively measuring the 3D Cartesian volumetric errors of the machine. The new sensing head uses capacitive sensors to gather data on the fly during a synchronized five-axis motion which lasts less than 2 min. Because the measured volumetric errors are strongly affected by the link geometric errors, they can be used to estimate the link errors through an iterative procedure based on an identification Jacobian matrix. The paper presents the new sensor, the identification model and the experimental validation. The approach allows all eight link errors i.e. the three squarenesses of linear axes and the four orientations and center lines offset of the rotary axes to be estimated with the proposed single setup test. The estimation approach is performed on a horizontal five-axis machine tool. Then, using the estimated link errors, the volumetric errors are predicted for axes combinations different from those used for the identification process. The estimated machine model correctly predicts 52–84% of the volumetric errors for the tested trajectories.

1. Introduction

The capability of five-axis machine tools in orienting and positioning the workpiece and the tool, relative to one another, makes them highly flexible. This reduces the need for multiple setups when machining complex parts and consequently reduces machine downtime which in turn increases productivity. These reasons explain the increasing demand for five-axis machines.

On the other hand, such machines are more prone to errors because of the increased complexity in their geometry and servo-control. Consequently, measuring methods are necessary to verify performance and generate diagnostic and compensation data to avoid the production of out of tolerance parts.

Measuring instruments have been developed and commercialized for linear axes but when rotary axes are present, measuring options are fewer. Laser interferometers with rotary indexers are commercially available for rotary axis indexing error measurement which covers only one of the six motion errors. Other commercially available instruments such as autocollimators and electronic levels, can measure up to two tilt errors of a rotary axis with its axis oriented vertically.

In 2002, Abasszadeh-Mir et al. concluded that eight link errors defined a five-axis machine tool geometry and they presented simulations results for the idea of using the telescoping magnetic double ball bar to estimate the link errors [1]. Since then, Tsutsumi and Saito and recently Dassanayake et al. also worked on the investigation of five-axis machine link errors using the double ball bar. They have used special multi-axis trajectories to estimate the five link errors associated with the rotary axes while the linear axes squarenesses are pre-measured using conventional approaches [2–4]. Zargarbashi and Mayer proposed a combination of double ball bar tests for a rotary axis and the two linear axes perpendicular to the rotary axis, to identify a rotary axis position and orientation [5].

Other instruments have also been proposed. Lei et al. developed and used a sensor, named 3D probe ball, to measure all three positional volumetric errors of five-axis machine tools [6,7]. The approach is used to estimate the link errors associated with the rotary axes, spindle block and tool holder. The squarenesses of the linear axes are not considered. Bringmann and Knapp proposed and tested a technique called "Chase-the-ball" using a ball artefact mounted at the tool holder and four linear probes on the machine table. They calibrated 14 parameters

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including the link errors and some positioning errors on a five-axis machine tool by measuring the tool center point deviations at a number of five-axis poses [8].

This paper presents a non-contact measuring instrument for on the fly Cartesian volumetric error measurement of five-axis machine tools using a programmed end point constraint procedure. The machine model and the link error parameters to be estimated are presented together with the identification procedure. Finally, experimental results are shown to assess the prediction capability of the estimated model.

2. Measuring instrument

The developed measuring instrument, called CapBall, mainly consists of a sensing head mounted in a tool holder in the spindle and a 19.05 mm diameter master ball mounted on the machine table (Fig. 1). The sensing head detects the relative 3D translation between the head and the ball. This provides a means to measure directly the volumetric errors of the machine. The sensing head consists of three capacitive sensors mounted with their measuring axes nominally orthogonal and intersecting. The sensors used are factory calibrated for a flat target with a measuring range of 1250 μm and a manufacturer's specified resolution of 50 nm. However, for a master ball (spherical target), as is the case here, the sensor's sensitivity (gain) increases and the measuring range decreases [9]. For the target used and after sampling and digital conversion the sensor readings have a resolution of approximately 300 nm.

The master ball is a precision steel ball glued to a cylindrical bar and mounted to the table with a magnetic base (Fig. 1). The ball must initially be centered at the sensors intersections to avoid exceeding the measuring range of the sensors during a test. The data sampling rate is set to 1000 Hz and a LabVIEW application is programmed to communicate with the sensors and save the measured data.

In a manner similar to [6–8], the CapBall uses a principle that was described by Bennett and Hollerbach in the robotic field [10] who suggested that "a manipulator may form a mobile closed-loop kinematic chain if it is redundant with respect to its endpoint constraint". In the present case, the endpoint constraints are not imposed but rather programmed. Thus, while the tool position relative to the workpiece table is kept nominally constant and because the machine has more than three joints (e.g. X, Y, Z, B and C), the two additional degrees of freedom allow the machine joints to be moved. The inability of the machine to maintain that relative position is measured, as volumetric errors, and provides useful data to analyze its performance and error sources. The rotary axes (B and C axes) impart a slinky-type motion to the ball and the linear axes (X, Y and Z axes) keep track of the ball trajectory thus ensuring the nominal coincidence of the sensors intersection and the ball. The non-contact sensors render possible not only quasi-static but also very high speed motions for dynamic error assessment. When the distance range between the sensor and the ball is limited to 200 μm and the eccentricity is within $\pm$125 μm, the measured distance error band is within 1 μm and the response non-linearity is 0.5%. The calibration of the orientation of the sensors axis with respect to the machine axes is conducted as a preliminary procedure by simply moving the machine linear axes one at a time and recording the sensor readings. This provides the three direction cosines to build a rotation matrix used to project the readings along the machine frame for the following tests.

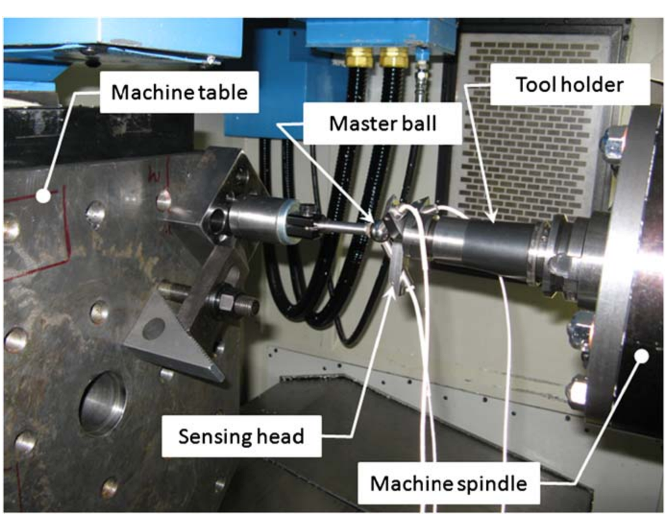

Fig. 1. Functional prototype consisting of a sensing head equipped with three capacitive sensors mounted at the tool holder and a master ball mounted on the machine table.

3. Machine error modeling

A five-axis machine tool of serial topology is a kinematic chain made of two rotary axes and three prismatic ones. As described by Everett and Suryohadiprojo [11], the number of fixed value parameters necessary to define the chain model, the robot base frame and the end effector frame is

$$N = 4R + 2P + 6, \tag{1}$$

where R is the number of rotary axes (here 2) and P is the number of prismatic axes (here 3), so $N = 20$. Using a maximum of six parameters to define the tool (for a cutting tool five are sufficient) and another six to locate the workpiece with respect to the workpiece branch axis, there remain eight link error parameters for the machine structure, excluding the spindle axis which is not considered here.

In Fig. 2, a five-axis machine kinematic chain schematic is shown with a WCBXFZYT topology (with W and T explicitly locating the workpiece and tool) in its nominal geometry where the linear axes are assumed mutually perpendicular and the rotary axes mutually intersecting and assumed perfectly aligned (angular wise) with the linear axes. In this situation one can define a nominal foundation frame at the intersection of the two rotary axes with its $\hat{\imath}_N$, $\hat{\jmath}_N$ and $\hat{k}_N$ directions cosines parallel to the nominal X, Y and Z linear axes of the machine.

In Fig. 3, the same machine is shown in an imperfect or deviated condition. The foundation frame now has its $\hat{\imath}_D$ direction parallel to the actual X-axis and its $\hat{k}_D$ direction perpendicular to the X direction and in a plane containing the real X and Z axes. The $\hat{\jmath}_D$ direction completes the orthonormal vector set of direction cosines. The Z-axis direction deviates from its ideal orthogonal condition with respect to the Y-axis by an angular error $\Delta\beta_Z$ around the $\hat{\jmath}_D$ direction. The Y-axis may also deviate from its pristine condition by two angular errors $\Delta\alpha_Y$ and $\Delta\gamma_Y$ around the $\hat{\imath}_Y$ and $\hat{k}_Y$ directions, respectively. These errors are the typical link errors of a three-axis machine tool, i.e. the three squarenesses. Note that linear axes do not require translational errors terms, only the direction of motion matters. Based on this discussion the link error twists of the linear axes are presented in Eqs. (2)–(4). Small displacement twist are well suited to represent the geometric errors of each axis as they have six components, three small translational and three small rotational displacements [12]:

$$^{\{X\}}\delta\tau_X = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T, \tag{2}$$