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Five axis machine tool volumetric error prediction through an indirect estimation of intra- and inter-axis error parameters by probing facets on a scale enriched uncalibrated indigenous artefact

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ABSTRACT

The volumetric accuracy of five-axis machine tools is affected by intra-axis geometric errors (error motions) and inter-axis geometric errors (axes relative position and orientation errors). Self-probing of uncalibrated facets on the existing machine tool table is proposed to provide the necessary data for the self-calibration of the machine error parameters and of the artefact geometry using an indirect approach. A set of 86 non-confounded coefficients are selected from the ordinary cubic polynomials used to model both the intra- and inter-axis errors. A scale bar is added to provide the isotropic scale factor. The estimated model is then used to predict the actual tool to workpiece position. Experimental trials are conducted on a five-axis horizontal machining centre using its original unmodified machine table as an artefact. For validation purposes only, the estimated artefact geometry is compared to accurate coordinate measuring machine (CMM) measurements. A study of the volumetric error predictive capability of the model for selected subsets of estimated error coefficients is also conducted.

1. Introduction

Five axis machine tools' ability to achieve both position and orientation control of the tool relative to the workpiece allows a reduction in the number of workpiece setups which increases productivity and, potentially, part quality. However, they are prone to numerous error sources, in part from the addition of two rotary axes, which also makes the calibration process more difficult. Volumetric errors between the tool and the workpiece are in part due to inter-axis geometric errors describing deviations in the position and orientation of successive axes average line of rotation or mean direction of translation in the machine kinematic chain and by intra-axis geometric error (also called error motions) parameters describing the deviations from perfect motion of each individual axis. The measurement of these errors is broadly conducted using direct and indirect approaches [1]. The direct methods to evaluate the geometric errors of a five-axis machine tool (e.g. laser interferometer, electronic level, autocollimator etc.) require precise setups, much time as well as specially trained personnel, thus there is relevance in seeking faster, simpler and less intrusive calibration procedures.

For five-axis machine tools in particular, indirect approaches are increasingly studied and used [2]. A so-called *R*-test device made of three analogous proximity sensors was used to conduct indirect geometric parameter estimation of a six axis parallel machine using discrete positions [3]. A similar device but using four sensors, the redundant forth sensor providing a data check, was later used to acquire discrete position readings to perform an indirect estimation of a five-axis machining centre axis alignments and relative linear scale gain errors [4]. A non-contact *R*-test with laser displacement sensors was recently developed to calibrate a five-axis machine [5]. A non-contact three capacitive sensor device was also studied to conduct quick on-the-fly data acquisition for indirect model estimation of axis alignments [6] and also to study the relative contribution of contouring errors, quasi-static geometric errors and dynamic geometric errors on a five-axis machine tool [7]. Volumetric errors on a five-axis machine tool involving the motion of two prismatic and one rotary axis were predicted using geometric and dynamic data. The geometric error parameters were estimated using an indirect on-the-fly approach [6] while the effect of servo errors for the linear axes is obtained from the machine controller encoder feedback. This study combined the geometric error model with servo errors to predict the machine volumetric behaviour [8].

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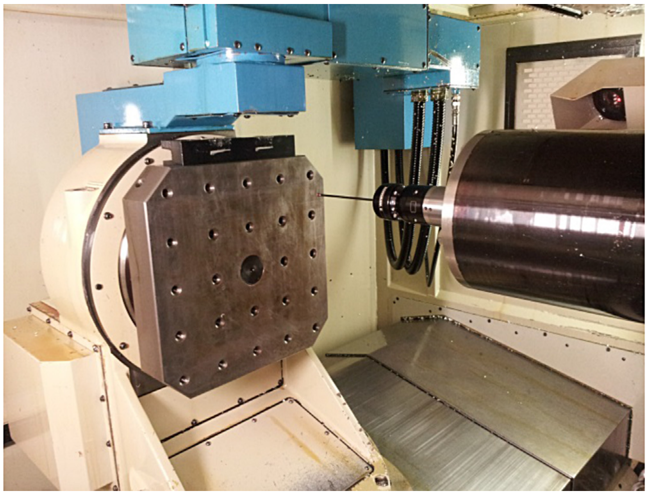

Fig. 1. Machine table, of a WCBXFZYST five-axis machine tool, used as indigenous artefact for probing.

Since most machines are now equipped with a touch trigger probe, it makes sense to investigate its use for machine performance evaluation and calibration as was done for coordinate measuring machines [9,10]. The SAMBA (Scale And Master Balls Artetact) method was proposed to estimate axis position and orientation errors, linear axis positioning error gains and spindle axis offsets on a five-axis machine tools by probing a scale bar and up to 24 master balls mounted at the tip of rods with different lengths fixed at uncalibrated positions on the machine table [11]. In [12], uncalibrated test pieces were mounted on the machine table and measured with the machine probe to calibrate the location errors of rotary axes of a five-axis machine tool assuming negligible error contributions from the linear axes. The method does not allow separating the influence of errors from the linear axes. The technique was later extended to the measurement of error motions of rotary axes [13]. The work in [12] and [13] requires the geometric errors of linear axes to be negligible and use a test piece externally brought into the machine tool's working envelop.

This paper proposes to use on-machine probing of only nominally known small faces (facets) already present on the machine standard table, thus creating an uncalibrated indigenous artefact, to simultaneously estimate inter-axis (axes location errors) and intra-axis (error motions) errors as cubic polynomials. Errors pertaining to all five axes and the spindle axis are simultaneously estimated. Because each facet is considered as a distinct feature and requires a single measurement, the approach is called "Touch ANd GO" or TANGO since a facet is touched for probing and then the next facet is sought for the next probing operation. A reference length is added to evaluate volumetric performance and absolute positioning errors for all three linear axes. The paper begins with a presentation of the overall TANGO concept followed by the associated mathematical models and error parameters to be estimated. Then, the test strategy is described. Results of preliminary tests mainly to assess the probing robustness are then presented followed by tests of the TANGO procedure and model validation in terms of volumetric error prediction capability.

2. Concept of an indigenous artefact

It is proposed to exploit existing machine table features which can be reached by the machine touch probe to gather the necessary volumetric raw data for machine error parameters' estimation.

As shown in Fig. 1, the machine table of the laboratory's Mitsui Seiki HU40T machining centre is an octagonal prism with nine nominally flat surfaces. Fig. 2 shows the selection of 26 small surface areas to be probed, called facets, each defined by a nominal target point on the surface and its own local nominal unit normal vector which altogether define the indigenous artefact. Since the exact machine table dimensions and geometric deviations are not known and are not required throughout the machine estimation process, the indigenous artefact is deemed uncalibrated. The concept could, in principle, equally use a fixture mounted on the machine or a machined part if it provides access to a sufficient number of facets.

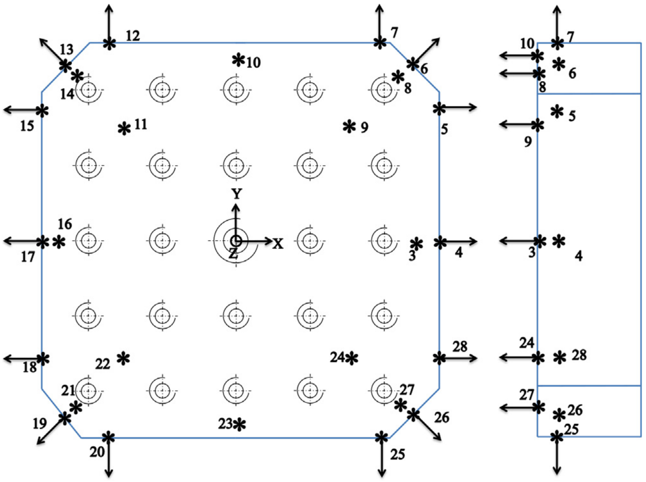

Fig. 2. Selection of facets defined as nominal points' coordinates on the surface and their respective nominal local unit normal vector. Facets are numbered from 3 to 28; number 1 and 2 are kept for the identification of the two spheres of the scale bar.

The rich set of facets allows probing of a subset of facets at numerous *B*- and *C*-axis indexation combinations.

3. Mathematical model

Considering inter-axis error parameters, rotary and linear axes require four and two parameters respectively to locate them in space, which yields a total of 14 parameters for the five axes of the machine tool [14] This number is obtained from the known equation for a serial chain mechanism,

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

where R is the number of rotary axes and P is the number of prismatic axes. However, removing consideration of the machine location in the universe, six parameters are removed leaving the usual eight inter-axis position and orientation errors of which seven are angular and one is translational. Using a parameter nomenclature based on [15] and [16] they are E_{AOB}, E_{COB}, E_{XOC}, E_{AOC}, E_{BOC}, E_{BOZ}, E_{AOY} and E_{COY}. For instance, E_{AOB} (squareness of *B*–*Z*) is the error in the orientation of axis *B* around the *X*-axis, an *A* rotation. Fig. 3 depicts those parameters for a WCBXFZYST horizontal machining centre where *W*, *F*, *S*, *T*, *C*, *B*, *X*, *Z*, *Y* stand for the workpiece, foundation, spindle, tool and *C*-, *B*-, *X*-, *Z*-, and *Y*-axis respectively. The eight parameters are defined as follows: the *X*-axis is first considered and has not alignment errors. Then the *Z*-axis has a squareness error to the *X*-axis, E_{B0Z}. Together they define the *XZ* plane. The *Y*-axis has potentially two out-of-squareness errors with respect to the *XZ* plane, one around *X* (E_{A0Y}) and one around Z (E_{C0Y}). The first rotary axis, *B*, has two out-of-squareness with respect to the *XZ* plane, E_{A0B} and E_{C0B}. The second rotary axis, *C*, has out-of-squarenesses relative to the *B*-axis and the *X*-axis as E_{A0C} and E_{B0C}. Because rotary axes have positions in space, they will in general not cross perfectly and so an *X* offset is defined for the *C*-axis with respect to the *B*-axis as E_{X0C}. These eight parameters locate