Indirect Measurement of Volumetric Accuracy for Three-Axis and Five-Axis Machine Tools

A Review

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Review:

Indirect Measurement of Volumetric Accuracy for Three-Axis and Five-Axis Machine Tools: A Review

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The volumetric accuracy of machine tools is represented by a map of position and orientation error vectors of the tool over the volume concerned. Numerical compensation for volumetric error is possible in many latest commercial CNCs for machine tools. This paper reviews indirect measurement schemes for machine tool kinematics, in which the tool center position is measured as the superposition of error motions of linear or rotary axes. Each error motion can be separately identified by best-fitting a set of measured tool center positions to the kinematic model of machine tools. Indirect measurement schemes for the kinematics of three orthogonal linear axes, as well as the five-axis kinematics with two rotary axes, will be reviewed.

Keywords: volumetric accuracy, indirect measurement, machine tools, kinematic model

1. Introduction

ISO TC39/SC2, a technical subcommittee in International Organization of Standardization (ISO), has lately been discussing the publication of a Technical Report (TR) on numerical compensation for geometric errors in machine tools [1]. This draft intends to "provide information for uniform identification and characterization of geometric errors of numerically controlled machine tools" [1]. Although this draft is still in a very early stage in the ISO publication process, such an effort clearly indicates the recognition by machine tool manufacturers and users of the importance of volumetric accuracy.

ISO/FDIS 230-1:2011 [2], in a revision process in ISO TC39/SC2, defines the term "volumetric accuracy" for a three-axis machine tool as "the maximum range of relative deviations between actual and ideal position in X-, Y- and Z-axis directions and the maximum range of orientation deviations for A-, B- and C-axis directions for X-, Y- and Z-axis motions in the volume concerned." The objective of volumetric error compensation is to cancel error in the Tool Center Position (TCP) at an arbitrary point in the work space by adjusting its command position.

On many commercial machine tool CNCs in today's market, it is common to implement numerical compensation for linear positioning error in a linear axis, often called "pitch error compensation," caused typically by the pitch error of a ball screw or linear encoder. Some CNCs numerically compensate for the straightness or squareness error in linear axes. Volumetric error compensation is a generalized extension of these simpler compensations. Many major CNC makers, e.g. Fanuc, Siemens, and Heidenhain, have lately commercialized the functionality of numerically compensating for volumetric error in linear and rotary axes. They typically adopt some form of model-based compensation, where the machine's kinematic model is assumed to cancel the predicted error given by this model at an arbitrary point. In [1], the "kinematic model" of machine tool is defined by "the model that describes the motion of rigid components within the machine tool structural loop and the joints that link them, without consideration to the forces that generates such motions." The general concept of numerical compensation has been common in coordinate measuring machines (CMMs), and its application to machine tools has long been studied [3–11].

According to Schwenke et al. [10], "direct" measurement of geometric error represents the analysis of single errors, such as linear positioning error and angular error of individual axes. For example, the linear positioning error of a linear axis is typically measured by using a laser interferometer [12]. One setup of this measurement measures only the linear positioning error of a single axis, minimizing the influence of other error motions. The key is to set up the measuring instrument so that only the targeted error motion influences measurement results. Direct measurement methodologies are well reviewed in [10], and many of them are widely accepted by machine tool builders [2]. For volumetric error compensation, the efficiency of the direct measurement can be a critical issue. For orthogonal three-axis machines, 3 linear displacement errors, 6 straightness errors, 3 squareness errors, and 6 angular errors must be measured by different setups to construct the machine's kinematic model.

"Indirect" measurement focuses on the tool tip location as the superposition of these single errors. In early attempts, indirect methods have been developed as a quick check of the machine's motion accuracy. More researchers recently reported the application of indirect measurement to the construction of the kinematic model or to the identification of (a part of) geometric error parameters. A typical example of indirect measurement widely done by machine tool builders is the circular test using the ball bar, described in ISO 230-4:2005 [13]. In a circular test, measured contour error profiles are influenced by many error motions of two linear axes, e.g., the positioning and straightness error of each axis and the squareness error between both axes. By best-fitting the machine's kinematic model to measured trajectories, many error motions can be estimated by a single circular test (see Section 3.1 for further review). This simple example illustrates a strong advantage of indirect measurement.

This paper reviews indirect measurement schemes for the identification of machine tool kinematic models. As a basis for numerical compensation, Section 2 reviews geometric error parameters and kinematic models of machine tools. Sections 3 reviews indirect measurement schemes for the kinematics of orthogonal three linear axes. Sections 4 reviews indirect measurement schemes for five-axis kinematics with two rotary axes. Section 5 presents conclusions.

2. Kinematic Models of Machine Tool

2.1. Geometric Error Parameters

Geometric errors in machine tools are caused by many factors, such as kinematic errors, thermo-mechanical errors, loads and load variations, dynamic forces, and motion control and control software [10]. This section reviews definitions and notation of geometric error parameters described in Annex A of ISO/FDIS 230-1:2011 [2].

The *reference straight line* of a linear axis of motion represents its direction with two orientations [2, 14]. *Location errors* of a linear axis represent orientations of its reference straight line in the reference coordinate system (called the *machine tool coordinate system* in [2]). As depicted in **Fig. 1**, for example, E_{A0Z} and E_{B0Z} respectively represent the orientation of the reference straight line of the Z-axis around X- and Y-axes of the machine tool coordinate system. Location errors of a rotary axis are defined analogously, representing the position and orientation of the *axis average line* of a rotary axis, i.e., the straight line representing the mean location and orientation of its axis of rotation [14]. In the literature, many other terms for location errors can be found, such as link error parameters [15], systematic deviations [16], and position independent geometric error parameters (PIGEPs) [17].

It must be emphasized that location errors represent "average" positions or orientations. For a linear axis, for example, the orientation of the trajectory of the moving component may vary from this "average" orientation as it moves (i.e., angular error motions). Such an error, as a function of the position of the axis, is represented by *component errors* in [14].

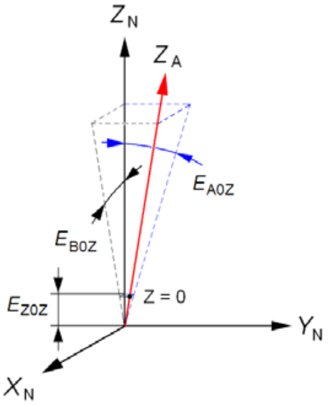


Fig. 1. Location errors for a linear axis (Z-axis) [2], where X_N, Y_N, and Z_N represent the machine tool coordinate system, Z_A represents the reference straight line of the moving component in the Z-direction.

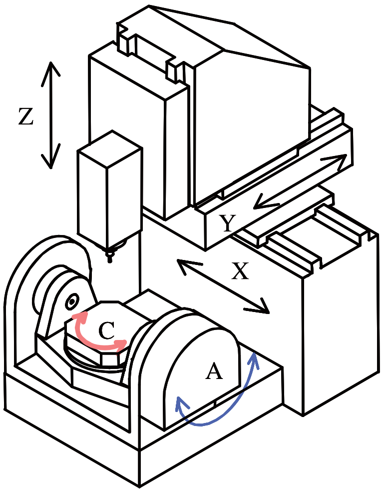


Fig. 2. Example of a five-axis configuration [18].

In the notation in Annex A of ISO/FDIS 230-1:2011 [2], geometric parameters are defined in reference to the machine tool coordinate system. Some works in the literature prefer geometric error parameters defined in the coordinate system attached to the "lower" axis in the machine's kinematic chain. Suppose, for example, the machine configuration depicted in **Fig. 2**, where the C-axis (rotary table) is mounted on the A-axis (swivelling axis). In "relative" notation, the orientation of the C-axis average line around the Y-axis, denoted by β_{CA} (notation in [19]), is defined with respect to the coordinate system attached to the A-axis average line, i.e., it represents the squareness of the C- to A-axis average line. The latest ISO/FDIS 230-1 additionally contains similar "relative" notation. Note that this notation defines error in the machine tool coordinate system, which differs from the "relative" notation in [19]. **Table 1** summarizes the notation of location errors in [2, 14, 19]. Clearly, both notations are easily convertible (in the example above, $\beta_{CA} = E_{B0C} - E_{B0A}$). "Relative" notation has, however, an advantage in simplifying the description of the kinematic

Table 1. Location errors notation.

Notation	Examples
"Relative" notation by Inasaki et al. [19]	$\delta y_{CA}, \alpha_{AX}$
The first (set of) character(s) represents the direction of deviation (δx, δy, and δz for linear deviations, and α, β, and γ for angular deviations). The symbol represents the position or the orientation of the coordinate system attached to the axis average line represented by the second character in the subscript, in reference to the coordinate system attached to the axis represented by the third character in the subscript.	
"Relative" notation in [2]	$E_{Y(0C)A}$
The first character after 'E' (for error) is the direction of deviation in the machine tool coordinate system. The second set of characters in parentheses is 0 (for location errors) accompanied with the chosen reference (datum) axis. The third character is the axis of concern.	
"Absolute" notation in [14]	E_{Y0A}, E_{A0A}
The first character after 'E' (for error) is the direction of deviation in the machine tool coordinate system. The second "0" represents the location error. The third character is the axis of concern.	

Table 2. Potential location errors for the machine tool in **Fig. 2** (for notation [2]).

C-axis	A-axis	X-axis	Y-axis	Z-axis	(C1)-spindle
E_{X0C}	–	E_{X0X}	–	–	$E_{X0(C1)}$
E_{Y0C}	E_{Y0A}	–	E_{Y0Y}	–	$E_{Y0(C1)}$
–	E_{Z0A}	–	–	E_{Z0Z}	–
E_{A0C}	E_{A0A}	–	E_{A0Y}	E_{A0Z}	$E_{A0(C1)}$
E_{B0C}	E_{B0A}	E_{B0X}	–	E_{B0Z}	$E_{B0(C1)}$
E_{C0A}	E_{C0A}	E_{C0X}	E_{C0Y}	–	–

Table 3. An example of a minimum set of location errors to fully characterize the 5-axis configuration shown in **Fig. 2** (for notation [2]). "0" is set by defining the coordinate system (here with primary axis X, secondary axis Y, origin X and Y in C, and origin Z in A). "(...)" are linear or angular zero positions that in general are set by the NC to any arbitrary value, but that must be checked for changes.

C-axis	A-axis	X-axis	Y-axis	Z-axis	(C1)-spindle
0	–	(E_{X0X})	–	–	$E_{X0(C1)}$
0	E_{Y0A}	–	(E_{Y0Y})	–	$E_{Y0(C1)}$
–	0	–	–	(E_{Z0Z})	–
E_{A0C}	(E_{A0A})	–	0	E_{A0Z}	$E_{A0(C1)}$
E_{B0C}	E_{B0A}	0	–	E_{B0Z}	$E_{B0(C1)}$
(E_{C0C})	E_{C0A}	0	E_{C0Y}	–	–

model, particularly for five-axis machine tools.

For "absolute" notation, the minimum set of location errors can be found by properly setting up the machine tool coordinate system, as is demonstrated in ISO/FDIS 230-1 [2]. For the machine configuration shown in **Fig. 2**, **Tables 2** and **3** illustrate the procedure for finding out the minimum set of location errors in absolute notation [2]. Analogous discussion also applies to the "relative" notation. **Table 4** show an example of sufficient set of location errors in relative notation in [19]. **Table 5** summarizes the description of this minimum set of location errors.

Table 4. An example of a minimum set of location errors to fully characterize the 5-axis configuration shown in **Fig. 2** (for notation [19]). The X-axis Coordinate System (CS), for example, represents the coordinate system with its X-axis attached to the machine tool's X-axis average line, its Y-axis aligned to the plane made by X- and Y-axis average lines, and its origin at the machine's origin (nominal intersection of C- and A-axes). For example, y_{AX} represents the Y-position of the A-axis CS with respect to the X-axis CS, i.e., the Y-offset of the A-axis center of rotation from the machine's origin.

C-axis CS	A-axis CS	X-axis CS	Y-axis CS	Z-axis CS	(C1)-spindle CS	
	δx_{CA}	–	–	–	$\delta x_{(C1)Z}$	
	δy_{CA}	δy_{AX}	–	–	$\delta y_{(C1)Z}$	
	–	δz_{AX}	–	–	–	
	–	(α_{AX})	α_{YX}	–	$\alpha_{(C1)Z}$	
	β_{CA}	β_{AX}	–	β_{ZY}	$\beta_{(C1)Z}$	
	(0)	γ_{AX}	γ_{YX}	–	–	

2.2. Kinematic Models

2.2.1. Kinematic Model of Three Nominal Orthogonal Linear Axes

The kinematic model of machine tools under the rigid-body assumption has been long studied [3, 19–24]. The objective of the kinematic model is to calculate the position and orientation of the tool in the workpiece coordinate system as the superposition of error motions of each axis. The *workpiece coordinate system* is the coordinate system attached to the work table.

Suppose the configuration of X, Y, and Z axes shown in **Fig. 2** as an example. When nominal X, Y, and Z-positions are given by x, y, and z, error in the TCP, $(e_x(x,y,z), e_y(x,y,z), e_z(x,y,z))$, and its orientation error, $(e_a(x,y,z), e_b(x,y,z), e_c(x,y,z))$, are given as follows [25], assuming that errors are defined at the TCP and all mea-

Table 5. Description and notation of location errors for the machine configuration in **Fig. 2**. Correspondence to symbols depends on the setup of the machine tool coordinate system; the setup of the machine tool coordinate system for symbols [14] is given in **Table 3**.

Symbol [19]	Symbol [2]	Symbol [14]	Description
Location errors associated with rotary axes			
α_{AX}		E_{A0A}	Initial angular positioning error of A-axis
β_{AX}	$E_{B(0X)A}$	E_{B0A}	Parallelism error of A- to X-axis around Y-axis
γ_{AX}	$E_{C(0X)A}$	E_{C0A}	Parallelism error of A- to X-axis around Z-axis
α_{CA}	$E_{B(0A)C}$	$E_{B0C} - E_{B0A}$	Squareness error of C- to A-axis
δx_{CA}		(E_{X0X})	Linear offset of C-axis in X direction
δy_{AX}		$E_{Y0A} - E_{Y0Y}$	Linear offset of A-axis in Y direction
δz_{AX}		(E_{Z0Z})	Linear offset of A-axis in Z direction
δy_{CA}	$E_{Y(0A)C}$	$-E_{Y0A}$	Linear offset of C-axis from A-axis in Y
Location errors associated with linear axes			
γ_{YX}	$E_{C(0X)Y}$	E_{C0Y}	Squareness error of Y- to X-axis
α_{YX}	$E_{A(0Y)Z}$	E_{A0Z}	Squareness error of Z- to Y-axis
β_{ZY}	$E_{B(0X)Z}$	E_{B0Z}	Squareness error of Z- to X-axis

surements for linear deviations are defined for this TCP:

$$\begin{aligned} e_x(x,y,z) &= E_{XX} + E_{XY} + E_{XZ} + [E_{BX} + E_{BY}] \cdot z \\ &\quad - E_{CX} \cdot y \\ e_y(x,y,z) &= E_{YX} + E_{YY} + E_{YZ} - [E_{AX} + E_{AY}] \cdot z \qquad (1) \\ e_z(x,y,z) &= E_{ZX} + E_{ZY} + E_{ZZ} + E_{AX} \cdot y \end{aligned}$$

$$\begin{aligned} e_a(x,y,z) &= E_{AX} + E_{AY} + E_{AZ} \\ e_b(x,y,z) &= E_{BX} + E_{BY} + E_{BZ} \quad \ldots\ldots \quad (2) \\ e_c(x,y,z) &= E_{CX} + E_{CY} + E_{CZ} \end{aligned}$$

where E_{Xi}, E_{Yi}, and E_{Zi} are the linear deviation of the axis i ($i = X$, Y, Z) in X, Y, and Z directions, respectively. E_{Ai}, E_{Bi}, and E_{Ci} are its angular deviation around X, Y, and Z directions. They are a function of the position of axis i, i.e., component errors. For simplification, the model above does not contain squareness errors. This model can be understood in either of the following ways:

(1) As illustrated in **Fig. 3**, for example, the yaw of the X-axis, i.e., E_{CX}, results in position error in the X-direction, $-E_{CX} \cdot y$, as the Y-axis moves to its nominal position, y. The model (1) can be derived by applying analogous analysis to the kinematic influence of each angular error.

(2) The Homogeneous Transformation Matrix (HTM) for converting the TCP in the workpiece coordinate system (in this case, the coordinate system attached to the TCP) to the machine tool coordinate system, ${}^rT_w \in \mathbf{R}^{4\times4}$, is given by:

$${}^rT_w = {}^xT_y {}^yT_z {}^zT_w \quad \ldots\ldots\ldots\ldots \quad (3)$$

where ${}^zT_w$ represents the HTM transforming the workpiece coordinate system to the coordinate system attached to the Z-axis, and is given by:

$$\begin{aligned} &{}^zT_w = \\ &D_a(E_{AZ}) D_b(E_{BZ}) D_c(E_{CZ}) D_x(E_{XZ}) D_y(E_{YZ}) D_z(E_{ZZ}) D_z(z) \\ &\quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4) \end{aligned}$$

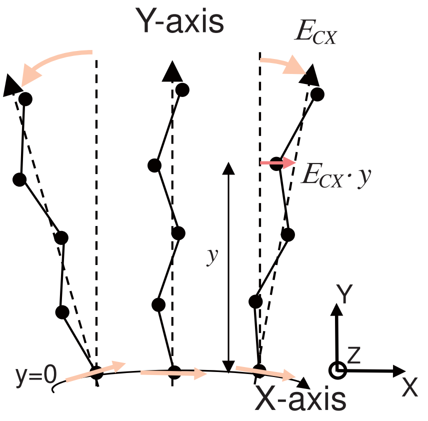


Fig. 3. Influence of X-axis yaw on Y-axis motion.

where $D_a(a)$, $D_b(b)$, and $D_c(c) \in \mathbf{R}^{4\times4}$ are the HTMs representing rotation around the X-, Y-, and Z-axes, respectively. $D_x(x)$, $D_y(y)$, and $D_z(z) \in \mathbf{R}^{4\times4}$ are the HTMs representing translation to the X-, Y-, and Z-axes, respectively. See, e.g., [19, 20] for their formulation. ${}^xT_y$ and ${}^yT_z$ in Eq. (3) are defined analogously. The TCP in the machine tool coordinate system can be represented by:

$$[\ e_x(x,y,z),\ \ e_y(x,y,z),\ \ e_z(x,y,z),\ \ 1\ ]^T = {}^r T_w \cdot {}^w p^* \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where ${}^wp^* = [0,0,0,1]^T$. Under the assumption that the machine's geometric errors are sufficiently small, Eq. (5) can be approximated by Eq. (1).

2.2.2. Kinematic Model of Five-Axis Machine Tools

The HTM-based derivation of kinematic models can be straightforwardly extended to the five-axis kinematics with two rotary axes [17, 19, 26]. Suppose the machine configuration shown in **Fig. 2**. The HTM representing transformation from the workpiece coordinate system to the machine tool coordinate system for given nominal A-

and C-angular positions, a and c, is given by:

$$\begin{aligned}
{}^rT_w &= {}^zT_y {}^yT_x {}^xT_a {}^aT_c {}^cT_w \\
{}^cT_w &= D_x(\delta x_{CA}) D_y(\delta y_{CA}) D_z(\delta z_{CA}) \\
&\quad D_a(\alpha_{CA}) D_b(\beta_{CA}) D_c(\gamma_{CA}) D_c(-c) \qquad . \qquad (6) \\
{}^aT_c &= D_x(\delta x_{AX}) D_y(\delta y_{AX}) D_z(\delta z_{AX}) \\
&\quad D_a(\alpha_{AX}) D_b(\beta_{AX}) D_c(\gamma_{AX}) D_b(-b)
\end{aligned}$$

All geometric error parameters are in "relative" notation, and a function of the position of the axis of concern, i.e., component errors.

The objective of indirect measurement is to identify (a part of) the geometric error parameters from a set of measured TCPs, $(e_x(x,y,z), e_y(x,y,z), e_z(x,y,z))$. The function for relating geometric error parameters to a set of TCPs can be analytically formulated from Eqs. (5) and (6). The linearization of this function is analytically presented in [27]. Its numerical calculation is also often used [28].

3. Indirect Measurement for Orthogonal Linear Axes

3.1. Circular Tests

The circular test, described in ISO 230-4:2005 [13], is now widely accepted by machine tool builders or users as an indirect measurement of the geometric accuracy of two orthogonal linear axes. It is typically performed by using the ball bar, first presented by Bryan [29], while a two-dimensional digital scale (see Section 3.3) is often used particularly for small-radius, high-speed tests [30]. Many other measuring instruments used to perform circular tests have been proposed, including two orthogonally aligned laser interferometers with a reference mirror [31], and a circular masterpiece and a probe [32, 33].

The circular test is not only a quick check of contouring accuracy, but also allows a user to quantitatively calibrate individual error motions of linear axes [32, 34–37]. It can be easily shown, for example, from the kinematic model (1) that the squareness error of two orthogonal linear axes makes the contour error profile elliptic tilted by 45°. In other words, the squareness error can be identified by best-fitting an ellipsoid to the measured contour error profile. This illustrates the simplest form of kinematic model identification by indirect measurement. The identification of the kinematic model based on circular tests have been presented in [38–42].

3.2. Diagonal and Step-Diagonal Tests

The diagonal test, described in ISO 230-6:2002 [43], measures TCP displacement in the direction of the body diagonal of the volume concerned by using a laser interferometer (see **Fig. 4**). ISO 230-6:2002 [43] states that the diagonal test "allows estimation of the volumetric performance of a machine tool," but "is not in itself a diagnostic test."

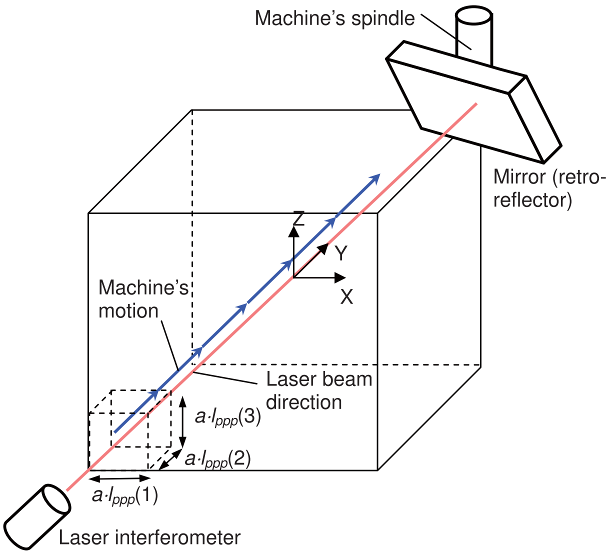


Fig. 4. Diagonal test [44].

For simplicity of formulation, assume that all angular errors are negligibly small. The diagonal displacement at the command position, (x,y,z), from its nominal distance is given from Eq. (1) by:

$$R_{ppp}(x,y,z) = l_{ppp} \cdot \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} e \qquad (7)$$

where $l_{ppp} \in \mathbf{R}^3$ is a unit vector representing the laser beam direction. $e = [E_{XX}, E_{YX}, E_{ZX}, E_{XY}, E_{YY}, E_{ZY}, E_{XZ}, E_{YZ}, E_{ZZ}]^T$ represents a set of component errors of linear axes; each geometric error parameter is a function of the position of the axis (x,y,z). In a diagonal test, command positions are given by $(x,y,z) = a \cdot l_{ppp} \cdot k$ $(k = -N, \ldots N)$. For all four diagonal tests, a total of $8N$ measured displacement data is obtained ($2N$ for each diagonal). The number of unknown geometric error parameters in this volume is $18N$. It is therefore clearly not possible to identify each geometric error parameter from four body diagonal measurements only.

Diagonal tests can estimate the squareness errors of linear axes [43, 45, 46]. When the aspect ratio of the measured volume is high, however, the sensitivity to measurement error or noise becomes high [47]. A modification of the diagonal test to assess more geometric error parameters is studied in [48].

The step-diagonal test, first presented by Wang et al. [49, 50], modifies the diagonal test by executing a diagonal as a sequence of single-axis motions, as is illustrated in **Fig. 5**. Since $3 \times 2N = 6N$ displacements are measured for each diagonal, Wang [49] claimed that all $18N$ geometric error parameters can be estimated by three body step-diagonal tests. Its experimental application has been reported in [51, 52].

Many researchers have discussed issues with the step-diagonal test [25, 47]. Ibaraki et al. [44, 53] clarified that an alignment error of laser and mirror directions cannot, in principle, be eliminated, and thus these misalignment

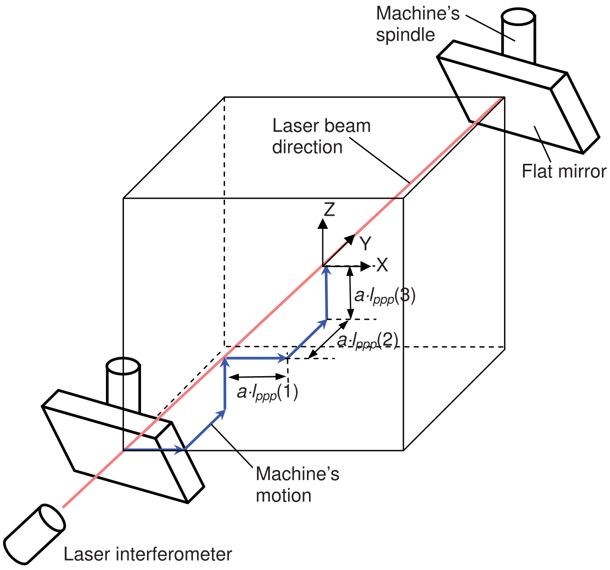


Fig. 5. Step-diagonal test [44].

parameters must be treated as unknown parameters to be identified. The modified formulation of the step-diagonal test was presented to identify all geometric error parameters even with the existence of these misalignment errors. Another critical issue is the machine's angular errors that are ignored in step-diagonal test formulation [25, 44, 54, 55]. Although some attempts to estimate angular errors were reported in [25, 56] from step-diagonal tests, their uncertainty is high in a typical environment. It is not recommended to apply the step-diagonal test to the calibration of geometric parameters unless the machine's angular errors are known to be sufficiently small.

Many researchers [57–60] presented the construction of the kinematic model from a set of linear displacement measurements on many lines including face or body diagonals. Such a scheme may, in practice, be effective, particularly for large machines, requiring only a laser interferometer to estimate angular errors through the kinematic model. Since many setup changes are needed, e.g., 15 lines in [59], attention must be paid to estimation uncertainties in practical applications.

3.3. Measurement of Artifacts

An established indirect measurement method uses calibrated artifacts in different positions in the volume. For CMMs, artifact-based calibrations are described in ISO 10360-2:2009 [61]. Its review can be found in [62]. Artifacts can be categorized by the number of spatial coordinates associated with principal calibrated features [63]. One-dimensional artifacts include gauge blocks (step gauges), ball bars, and one-dimensional ball arrays [64, 65]. Two-dimensional artifacts include ball plates [66], hole plates [67], and 2D step gauges [68].

The three-dimensional ball plate is presented for machine tool calibration in [69, 70] (see **Fig. 6**). By measuring the precalibrated position of spheres by using, e.g., a nest of displacement sensors [65, 69] attached to the machine's spindle, position error vector, $(e_x(x,y,z), e_y(x,y,z), e_z(x,y,z))$ can be measured for each sphere's calibrated position, (x,y,z).

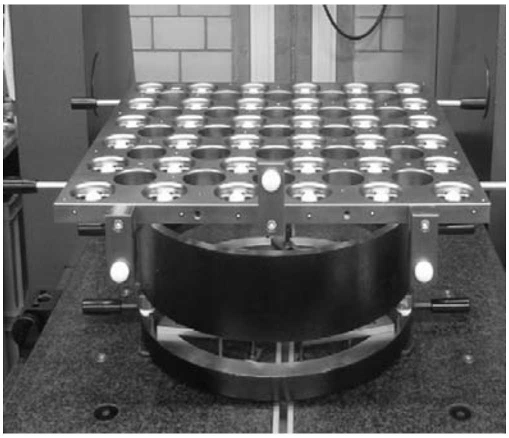


Fig. 6. Ball plate [69, 70].

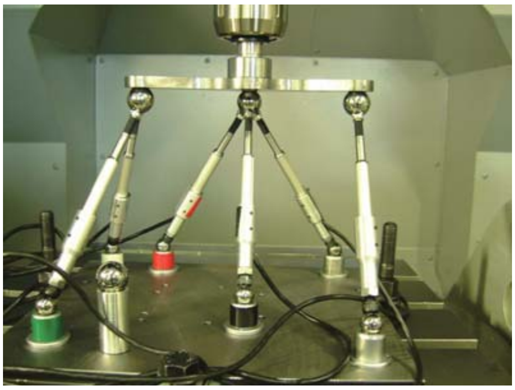


Fig. 7. 6-DOF parallel link mechanism for machine tool calibration [88].

The two-dimensional digital scale, or the cross grid encoder, uses a grid as a reference artifact [71, 72]. Its application to machine tools error calibration can be found in many works [73–77]. Vision-based measurement of a grid has the advantage of performing measurement even when the target is rotated [78].

An important issue in artifact-based measurement is the calibration of the artifact. Self-calibration approaches are typically used [70, 79–82]. For the calibration of large machine tools, a large artifact of the required geometric accuracy is needed, which is often difficult and/or expensive.

3.4. Passive Links

Calibrated kinematics of the link mechanism attached to and passively driven by the machine to be measured can be used as a reference. Ushio et al. [83, 84] presented a serial link mechanism of three orthogonal linear axes for machine tool calibration. Serial links with rotary joints [85–87] and parallel link mechanisms [88, 89] were also studied for machine tool calibration. As an example, **Fig. 7** shows the parallel link mechanism in [88]. The application of the laser ball bar, in which the distance between spindle-side and table-side spheres is measured by a laser interferometer, as a parallel link mechanism for three-dimensional measurement has been presented [90–92]. The concept of such a parallel link for three-dimensional measurement is closely related to the multilateration measurement to be presented in the following subsection.

Unlike many artifact-based measurements in the previous subsection, passive links allow the measurement of the TCP at arbitrary points within its working volume. A common issue is the calibration of the kinematics of the link mechanism. It is, furthermore, in practice difficult to construct passive links of the required uncertainty for large machines.

A potential way to deal with the calibration of kinematics is to define the parameters of the kinematics as additional unknowns in the model and to evaluate these unknowns together with the parameters of the machine tool. It is essentially analogous to the multilateration measurement presented in the following subsection.

3.5. Tracking Interferometer

The tracking interferometer (the term in [2]), or the laser tracker, is a laser interferometer with a steering mechanism to change the laser beam direction to track a target retroreflector (typically a cat's eye [93]). Three-dimensional position measurement of the TCP can be done by conventional commercial laser trackers, from, e.g., Leica Geosystems, Faro, and Automated Precision Inc. (API), by measuring the distance (displacement) to the target and the direction of the laser beam [94, 95]. Since its angular measurement uncertainty directly contributes to the measuring uncertainty of the target's position, it is typically difficult to ensure its measuring uncertainty small enough to evaluate machine tools.

The application of tracking interferometers to multilateration-based measurement, in which the target's three-dimensional position is estimated by the distance (displacement) from typically four or more tracking interferometers to the target, has been studied for machine tool calibration [96–100]. Its commercial product has been recently introduced (Etalon AG [98, 101]). **Fig. 8** shows the tracking interferometer developed in [100]. Its application to machine tool calibration was studied by one of the authors [102].

Suppose that the i-th target position is given by $x_i \in \mathbf{R}^3$ $(i = 1,\dots N)$ and the j-th tracker position is given by $X_j \in \mathbf{R}^3$ $(j = 1 \sim 4)$, as illustrated in **Fig. 9**. The coordinate system is defined so that a total of six parameters in X_j $(j = 1 \sim 4)$ is fixed. The problem of calculating target positions, x_i $(i = 1,\dots N)$, is parameterized as the following minimization problem:

$$\min_{x_i, X_j} \sum_{i=1\sim4, j=1\sim N} \left\{ (\|x_i - X_j\| - \|x_1 - X_j\|) - d_{ij} \right\}^2 \quad . \qquad (8)$$

where $d_{ij} \in \mathbf{R}$ represents the laser displacement measured by the j-th tracker at the i-th target position. Since this is a nonconvex problem, an iterative linearization-based approach is typically used to locally solve it [102]. Direct identification of geometric error parameters in Eq. (1) is also possible [98] by combining Eq. (8) with the machine's kinematic model (1).

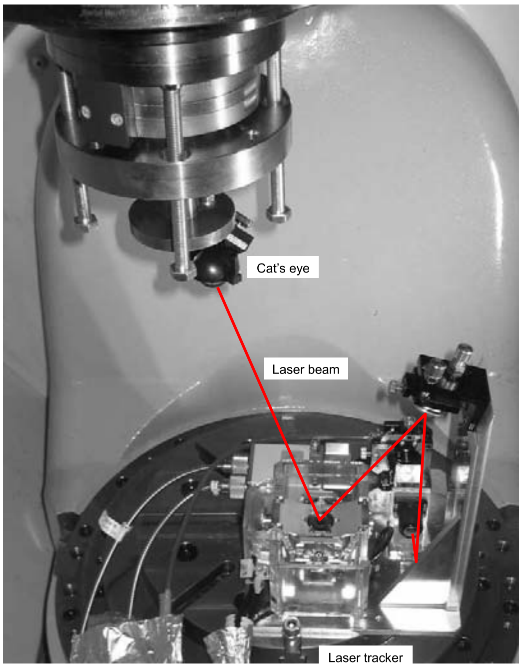


Fig. 8. Tracking interferometer [100, 102].

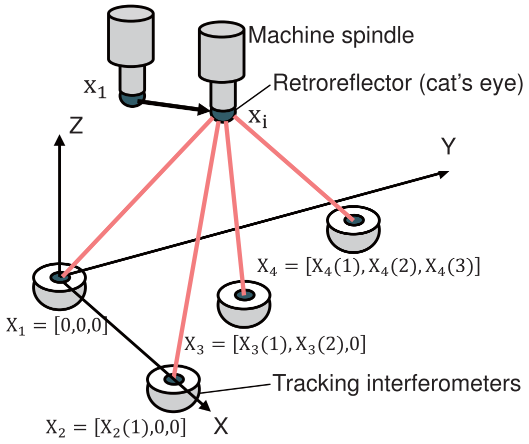


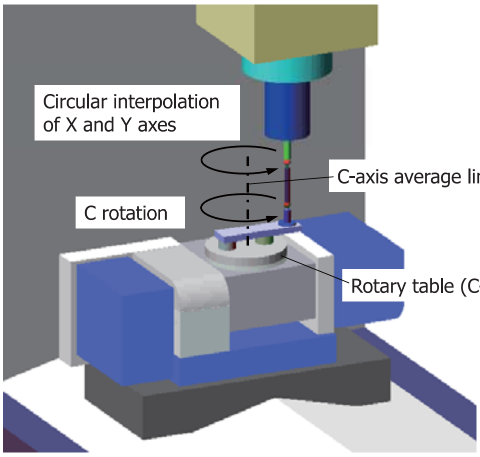
Fig. 9. Configuration of multilateration-based measurement by four tracking interferometers [102].

Tracking interferometers enable the target's three-dimensional position at arbitrary locations to be measured within the work space. The uncertainty of multilateration-based measurement must be carefully studied. Uncertainty in estimated target positions may vary significantly, depending on the locations of tracking interferometers and the measuring points selected [98, 103].

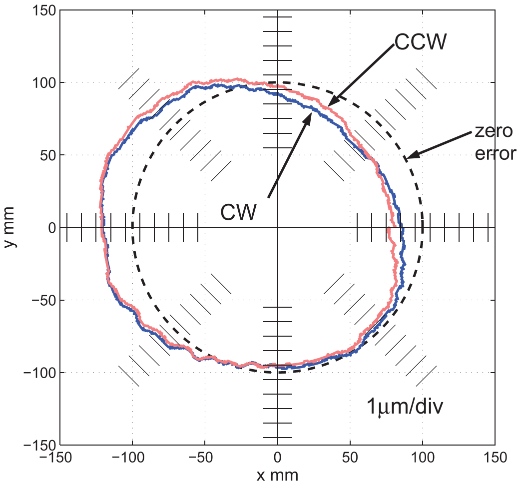
4. Indirect Measurement for Five-Axis Kinematics with Rotary Axes

4.1. Ball Bar

ISO 10791-1 to -3 [104–106] describe quasi-static measurements for five-axis machining centers with two ro-



(a) Schematic of ball bar test



(b) An example of measured error profile

Fig. 10. A ball bar test to calibrate orientations of the C-axis average line (test BK2 in [109]).

tary axes on the spindle side. Their revision is currently being discussed by ISO TC39/SC2 [107] to include analogous tests for other configurations of five-axis machines. Dynamic interpolation tests described in ISO 10761-6:1998 [108] are also in a revision process in ISO TC39/SC2 [109]. Many tests added to ISO/CD 10791-6 [109] can be seen as indirect measurement focusing on the calibration of location errors of rotary axes.

Many research efforts have been reported on the extension of the ball bar measurement to calibrate the location errors of rotary axes [16, 110–118]. **Fig. 10(a)**, for example, illustrates a ball bar test described in BK2 of ISO/CD 10791-6 [109]. When squareness error of the C-axis average line to the X-axis (or Y-axis) average line exists, the measured displacement profile in a polar plot for the C-axis angular position is shifted in the X- (or Y-) direction, as is shown by the example of a measured error profile in **Fig. 10(b)**. This illustrates the basic idea of these approaches. The application to various configurations of rotary axes has been reported, e.g., five-axis machines with a universal spindle [119], mill-turn centers [120, 121], and five-axis machines with an angular swivel head [122].

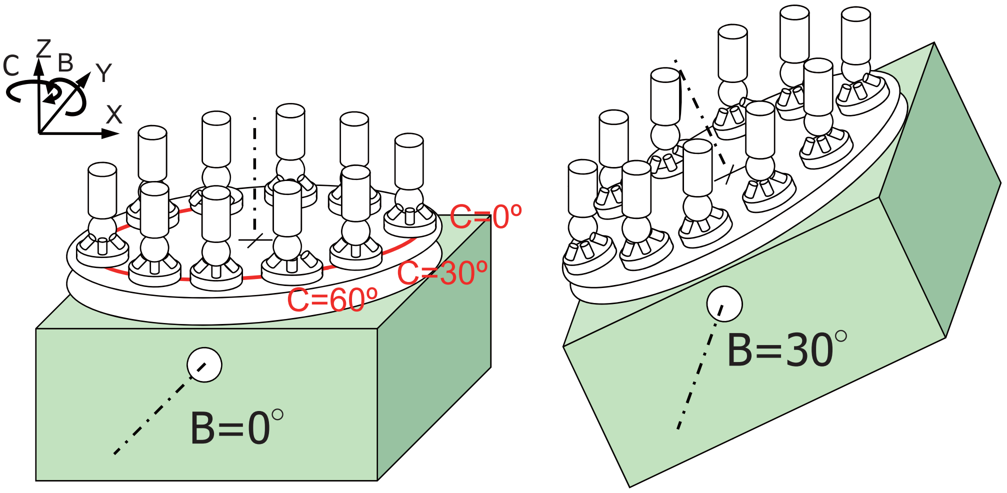
Since ball bar measurement is one-dimensional, it often requires at least a couple of different setups to identify all location errors. It also requires an experienced operator to perform the measurement, and its full automation is difficult.

Fig. 11. R-test prototype [130].

The test example in **Fig. 10** targets a single error source. More complex tests requiring synchronous four- or five-axis motion can potentially identify a larger set of location errors by best-fitting the measured profile to the kinematic model [18, 123]. The ball bar test equivalent to the cone frustum machining test [124] (see Section 4.5), which also requires synchronous 5-axis motion, is included in ISO/CD 10791-6 [109]. Yumiza et al. presented a test under the synchronization of one rotary axis and one linear axis with the main interest in dynamic synchronization error [125, 126]. Lei et al. [127] also presented ball bar tests focusing more on dynamic synchronization error in linear and rotary axes.

4.2. R-Test

As is described in ISO/CD 10791-6 [109], many of the ball bar tests presented above can be equivalently done by using a precision sphere and a linear displacement sensor [128]. The three-dimensional displacement of the sphere can be measured by using a nest of three (or more) linear displacement sensors. Weikert [129], Bringmann, and Knapp [28] presented the "R-Test" based on this concept. **Fig. 11** shows a prototype R-test device by Ibaraki et al. [130]. A nest of three displacement sensors is fixed on a rotary table to measure the three-dimensional displacement of a precision sphere attached to the machine spindle relative to the work table. IBS Precision Engineering [131] and Fidia [132] recently commercialized an R-test device for machine tool calibration. Zargarbashi and Mayer [15, 133, 134] presented an analogous sensors nest by using three noncontact capacitive sensors. The "3D Ball" presented by Lei and Hsu [135, 136] is also based on the same concept. The nest of three orthogonally aligned displacement sensors presented in ISO 230-7:2006 [14]



(a) At $B = 0°$, C-axis is indexed at various angles, e.g. at every 30°. X- and Y-axes are positioned so that the sphere follows the sensors nest.

(b) Same measurement is done at various B angles, e.g. at every 30°.

Fig. 12. Example of R-test cycle [27, 28].

can be seen the same in principle [137]. As was discussed in [138], when a sphere-ended contact probe or a noncontact displacement sensor is used for the R-test, the calculation of the sphere displacement becomes more complex. (Hong and Ibaraki [139] started a study on a noncontact R-test device with laser displacement sensors.) Conventional R-test devices thus have contact displacement sensors with a flat-ended probe.

Figure 12 illustrates an example of the R-test measurement cycle [27, 28]. Compared to the ball bar test in **Fig. 10(a)**, the R-test obtains three-dimensional TCP displacements at various B and C angles without the setup being changed. This efficiency is a strong potential advantage of the R-test. Many past works [15, 28, 136] presented the application of the R-test to the identification of location errors of rotary axes by best-fitting measured data to the five-axis kinematic model. Ibaraki et al. presented its extension to numerical mapping of component errors of rotary axes [27] as well as their graphical presentation for more intuitive understanding of rotary axes error motions [130].

Most of measurement schemes presented in sections 4.1 to 4.5 measure the TCP relative to the work table under the synchronous motion of linear and rotary axes. The measured displacement profile is therefore influenced by not only error motions of rotary axes, but also error motions of linear axes. For the calibration of rotary axes, many past studies assume that error motions of linear axes are sufficiently small. A uncertainty study is essential for assessing the calibration reliability under the influence of linear axis error motions [134, 140, 141]. Ibaraki et al. [130] showed that error motions of rotary axes can be calibrated with the minimum influence of linear axes error motions, when the sphere is placed nominally on the axis average line of a rotary table. It is in principle equivalent to the test described in ISO 230-7:2006 [14].

Beyond static geometric errors, some recent work presented R-test applications to the three-dimensional measurement of dynamic error, with particular interest in the cross-talk [142] and the reversal of a rotary axis [143], and thermal influence on rotary axis error motions [144].

4.3. Probing of Artifacts

Many machine tools in today's market have on-machine probing capability, usually used for part setup compensation. High-accuracy touch-trigger probes for machine tools, which typically have one-directional measurement repeatability less than 1 μm, are available from some vendors. ISO TC39/SC2 has also been discussing the standardization of test codes for measuring the performance of such a touch-trigger probe (ISO 230-10:2011 [145]). By its nature, such a probe has good communication capability with a CNC system, which potentially facilitates the automation of error calibration and compensation.

Tests presented in Sections 4.1 and 4.2 can be done by using such a probe when tests are static. ISO 10360-3:2000 [146] describes such a test for CMMs with a rotary table as the fourth axis. Probe-based calibration of offset errors of rotary axis average lines can be done using some commercial CNCs [147, 148]. Its extension to a set of all location errors of rotary axes has been reported in the literature [149–152]. While tests in Sections 4.1 and 4.2 continuously measure a single point (sphere center), quasi-static tests can measure the inclination of a rotary axis by probing multiple points using an artifact of rectangular column geometry [151] or multiple artifacts [153] (see **Fig. 13**).

4.4. Tracking Interferometer

Unlike many other indirect schemes reviewed in this paper, the tracking interferometer reviewed in Section 3.5

Fig. 13. Setup of three artifacts to calibrate translational and tilt error motions of rotary axes [153].

can potentially be applied to the direct measurement of rotary axis error motions at arbitrary locations without requiring the synchronous motion of linear axes [101]. More studies will be needed, however. A simpler one-dimensional version of a tracking interferometer for measuring a rotary axis can be found in the literature [154].

4.5. Machining Tests

Typical machine tool users are concerned more with machine's accuracy in performing actual machining. National Aerospace Standard (NAS) 979 [155] describes a five-axis machining test of a cone frustum, which is widely accepted as a final performance test by machine tool builders. Its inclusion in ISO/CD 10791-7:2011 [156] is currently under discussion in ISO TC39/SC2. Some researchers present sensitivity analysis of location errors of rotary axes on the geometric accuracy of the machined cone frustum workpiece, with a particular interest in the influence of workpiece location and orientation [157–159]. Matsushita et al. [160] presented the identification of all location errors from finished cone frustum workpieces when they are machined at three different positions. It is, however, generally not possible to separately identify each location error using a single cone frustum machining test. Hong et al. [161] showed that many error motions of rotary axes do not significantly influence the circularity error of the finished workpiece, except for the center offset of rotary axes or its shift due to the rotation of a swivelling axis. In other words, the cone frustum machining test is not suitable for indirect measurement of the machine's geometric errors.

NCG recommendation 2005 [162] also presents a test workpiece for five-axis machining, but the diagnosis of error sources is not in its main focus. The machining test of a truncated pyramid proposed by Saiki et al. [163] is more sensitive to dynamic synchronization errors of rotary and linear axes, although quantitative calibration of each error source is as difficult as for the cone frustum test. The five-axis machining test of a square column cavity is presented in [164].

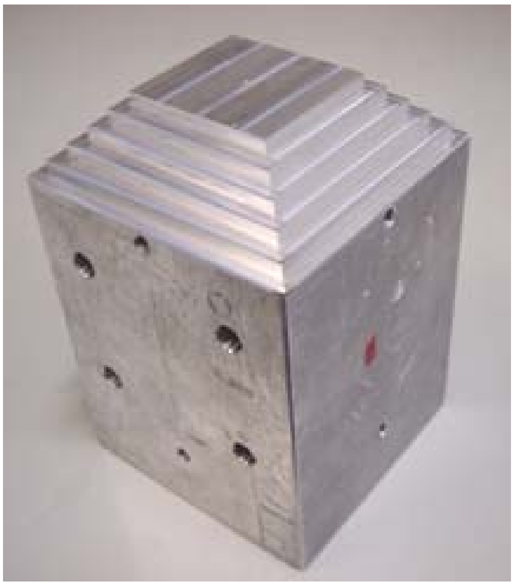


Fig. 14. Workpiece for calibrating location errors of rotary axes [171].

ISO/CD 10791-7:2011 [156] contains simpler five-axis tests of boring holes. Analogous simpler cutting tests, e.g., planar grinding by a grinding wheel [165] or grooving by a single-point cutting tool [166], can be used as a probe to calibrate the position of rotary axis average lines. To extend this concept, some researchers propose machining tests as an indirect measurement of the machine's geometric error parameters. The machining test presented by Ohashi et al. [167] can be seen as an extension of the three-axis machining test described in ISO 10791-7:2006 [168] (ISO 13041-6:2005 [169] for turning centers) to five-axis machining. Morimoto et al. [170] presented a planar machining test using a nonrotating tool to minimize the influence of tool geometries or the machine spindle's heat generation on the finished workpiece. Ibaraki et al. [171] presented a machining test to identify all location errors of rotary axes. Each face of the workpiece in **Fig. 14** is machined by using a square end mill at various index angles of rotary axes. The influence of each location error is parameterized by the geometric relationship of two machined faces. Yamamoto et al. [172, 173] presented a calibration scheme of location errors through grooving by using a ball end mill.

5. Concluding Remarks

Volumetric error compensation for CMMs has been an established practice for many years, and its application has been increasingly extended to machine tools [10]. Today's pioneering applications are large machine tools used typically in the aerospace and power industries due to higher accuracy demand and also requirement for reducing the cost of mechanical accuracy. In large machines, major contributors to volumetric accuracies are often angular errors of linear axes. The same observation applies to five-axis machines, where tilt error motions of a rotary axis cause increasingly large positioning error as the distance from the axis of rotation increases. The maximum benefit of numerical compensation can be achieved in such angular or tilt error motions. Knowledge of metrology and kinematic models becomes essential for mapping and then compensating systematic volumetric error, particularly that due to angular error motions. This paper first reviewed the fundamentals of kinematic modeling. The objective of indirect measurement methodologies is to identify the machine's geometric error parameters by best-fitting measured results to the machine's kinematic model.

The ultimate goal of indirect measurement is to measure the three-dimensional position of the TCP at arbitrary points over the entire work space in an accurate and efficient manner. Almost all measurement schemes reviewed in this paper have many limitations. They can be categorized as follows:

(1) *Limitations in measurable dimension*:
Ball bar tests (Sections 3.1 and 4.1) measure only one-dimensional displacement of the TCP. Diagonal and step-diagonal tests (Section 3.2) are also one-dimensional. Machining tests (Section 4.5) evaluate only the projection of the machine's geometric error onto the machined workpiece surface. In these approaches, three-dimensional volumetric error can be assessed only through the machine's kinematic model.

(2) *Limitations in measurable positions*:
Artifact-based measurement (Section 3.3) can measure only at pre-calibrated positions, e.g., spheres in the ball plate. Measurable trajectories for ball bar tests (Sections 3.1 and 4.1) are determined by sphere position fixed on the machine table. Passive links (Section 3.4) and two-dimensional scales (Section 3.3) can measure arbitrary positions, although the measurable volume is limited by strokes of reference links or the size of the grid plate. Tracking interferometers can measure arbitrary positions in larger workspace, although its measurement uncertainty may vary significantly depending on the target position.

(3) *Capability of separating each axis*:
Ball bar tests for rotary axes (Section 3.1) and R-tests (Section 3.2) are typically done with two (or three) linear axes driven synchronously with a rotary axis of interest. The measurement result will naturally be affected by all axes involved. Most schemes reviewed in Section 4 are the same in that the separation of error motions of linear axes and rotary axes is a critical issue in kinematic model construction.

(4) *Capability of measuring angular errors*:
Ball bar tests (Sections 3.1 and 4.1), R-tests (Section 4.2), and ball-plate-based calibration (Section 3.2), measure only the position of a reference sphere center, because the sphere does not define any orientation. Angular error motions of the machine can be estimated only through best-fitting to the kinematic model using measured data at multiple points. Quasi-static measurement of artifact (Section 4.3) and machining tests (Section 4.5) can directly assess angular errors.

Attention must be paid to the essential difference between CMM calibration and machine tool calibration. A spherical probe is used on a CMM in general. Angular errors therefore need not be compensated for fully, but only the linear effects of angular errors to the center position of the probing sphere. Any compensation for a CMM can be limited to compensation for the position of the TCP as described in Eq. (1).

No spherical tools are used in general on a machine tool, but cylindrical or plane milling tools and grinding tools, etc., are used, so angular errors must be compensated for fully, i.e., angular errors should be compensated for mechanically or by additional angular movement of NC rotary axes. Full compensation for a machine tool must implement compensation for the position of the TCP according to Eq. (1), as well as compensation for orientation errors according to Eq. (2).

Compensation of machine tools must deal with geometric errors varying due to thermal changes and load effects. Efficiency and automation are keys to error calibration schemes to be applied to a periodic check of volumetric accuracy or to the updating of numerical compensation. Such a periodic update may be done by service engineers or machine tool users. Basic knowledge of indirect metrologies and best-fit approaches to kinematic models will be essential to such an application.

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