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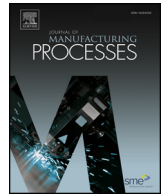
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Design and Analysis of a Built-in Yaw Measurement System Using Dual Linear Scales for Automatic Machine Tool Error Compensation

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ABSTRACT

In order to achieve high accuracy of computer numerical controlled (CNC) machine tools, various error compensation functions are implemented in the CNC control system. However, these error compensations are not designed to track the dynamic change in accuracies, such as thermal distortion or aging deterioration, during a machining process. To compensate for the dynamic change in accuracy, a built-in automatic measurement and compensation system based on dual linear scales was proposed, and its performance requirement was analyzed. Based on the analysis, a physical prototype was developed, and its feasibility was investigated by a series of experiments. The results showed that the measurement with the linear scale system agreed with a conventional measurement method within the uncertainty estimated at the design stage. In a subsequent experiment, the accuracy compensation was performed based on the measurement value. With compensation, the maximum accuracy deterioration was successfully suppressed from 22 to 3 μm .

Introduction

CNC machine tools and the importance of their accuracy

Computer numerical controlled (CNC) machine tools, or simply machine tools, play one of the most fundamental roles in modern society in producing various types of industrial products. In metal cutting by a machine tool, material removal is achieved by defining relative motions between a cutting tool and a workpiece during their physical interference. Due to the physical interactions, the machine motions are directly copied onto the workpiece, which determines the geometric and dimensional accuracies of the machined products. The accuracy of the products never transcends that of the machine tools used for manufacturing the products. Due to this "copying principle" [1], in order to obtain highly accurate products, there has been a continuous demand for machine tools with higher accuracy. Therefore, building machine tools with high accuracy has been a major task of machine tool manufacturers. Modern CNC machine tools are expected to have an accuracy of 1 μm , and higher precision would be expected in the future [2]. In order to carefully build accurate machine tools with differentiating precision and accuracy, engineers and researchers have

developed various technologies and techniques to eliminate the influence of error sources at the design and assembly stage. Structural analysis [3], temperature control of machines [4], or employment of alternative materials for machine structures [5] are just a few examples of them.

Error compensation technology to achieve high precision

Even with these technologies, building a machine tool with an accuracy on the order of 1 μm is still a challenging task because the accuracy of machine tools deteriorates due to internal and external error sources. Thus, another approach, so-called error compensation, plays a vital role in achieving high precision. Error compensation is a technology for removing the residual error by adjusting the motion of the machine to cancel the error that cannot be eliminated by the previously mentioned design and assembly technologies [6].

A mass production process is a typical use of CNC machine tools. In a mass production process, the whole machining process of the workpiece is divided into multiple subprocesses, such as rough milling, finish milling, and drilling. A CNC machine tool is dedicated to each of these subprocesses, and the machine tool repeats the subprocess to the

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Nomenclature

$D_{(X,Y,Z)}$	distance between the two linear scales installed on the X-, Y-, or Z-axis
E_{ij}	error of a linear axis component, where i indicates the direction of the error and j indicates the axis of the component
$H_{(X,Y,Z)}$	homogeneous transformation matrix for the X-, Y-, or Z-axis
L	distance traveled by a linear axis component from the origin of the axis

workpieces that flow in the production line. Therefore, the machine tool is expected to repeat the same motion with the same accuracy during its operating time. The accuracy of the repetitive motion of the machine tool is commonly called the repeatability of motion.

If a machine has a high degree of repeatability, it is expected that the machine will move with the same amount of error as the previous motion. Therefore, by recording the information and subtracting the same amount from the position command, the error is canceled out in the subsequent motion.

Most of the current error compensation technologies are based on this idea. A conventional error compensation procedure begins with the measurement of the error to be compensated. The measured error data are then recorded in the CNC controller as compensation parameters. During the subsequent machining process, the CNC controller makes the compensation based on the recorded parameters.

Current CNC controller vendors provide error compensation functions for typical errors, such as backlash compensation, ball-screw pitch error compensation, and straightness error compensation [7]. These functions are pre-installed in the controller, and the parameters are determined by the dedicated measurement methods. CNC machine tool manufacturers perform the measurement and set the parameters for the individual machine in the production process. In addition to the error compensation function provided by the CNC controller vendors, CNC machine tool manufacturers also develop unique error compensation functions by themselves. For example, Okuma Co., Ltd., offers a geometric error compensation function for its five-axis machine tool [8]. Thus, error compensation is an essential function of modern high-precision machine tools.

Problem of conventional error compensation

The error compensation process typically assumes that the machine's motion error is always the same as the recorded data. As long as the machine keeps its motion repeatability, the error compensation is able to cancel the error, and the machine can achieve high precision. However, in reality, the repeatability of the machine tool continuously changes during the operation due to such aspects as thermal distortion and aging degradation of bearings. Let us call this the "dynamic change" in repeatability as it is time-variant behavior. Once the dynamic change occurs, the error compensation will no longer be valid, and a certain number of errors will remain uncompensated. The uncompensated errors are copied onto the workpiece, resulting in excessive inaccuracy of the machined workpiece geometry. This is, of course, a critical issue for the machine user's productivity. In order to preserve the accuracy of the machine, the error compensation parameters need to be kept up to date to track the dynamic change in the repeatability.

However, conventional error compensation methods are manual labor and not designed for this dynamic compensation. In order to determine the parameters for the compensation functions, accuracy tests need to be performed on the machine by using measurement devices such as laser interferometers [9], double ball bar (DBB) systems [10], and laser trackers [11]. However, such measurement devices are

designed for offline measurement, which requires the machine to stop any machining process during the measurement. Stopping the machine in the production line is, of course, an undesirable interruption in the production for the machine user. Furthermore, the measurement typically takes a couple of hours, and some can take up to a whole day. The measurement time is too long to compensate for short-term accuracy deterioration, such as thermal or cutting-force-induced errors.

Objective of this research

As discussed so far, the accuracy compensation of machine tools are manual and time-consuming process and cannot track the dynamic change in repeatability. This is a substantial drag on automation, labor saving, and process integration of production processes.

The objective of this research is to develop a dynamic error compensation system. To realize that, the error measurement process is automated by building measurement sensors in the machine. By building the sensors in the machine, the manual process in performing conventional error measurement will be eliminated. Since the measurement system is built in the machine, users do not need to prepare expensive measurement devices, and the accuracy data can be obtained as internal data of the machine. Appropriately installing the sensors so that they do not interfere with the machining process makes it possible to do a measurement faster and under actual cutting conditions. With this system, the machine can automatically inspect its own accuracy and update the compensation parameter as soon as the accuracy deteriorates. In this sense, the new compensation procedure is more dynamic than the conventional one. Thus, in this study, the system is called a dynamic error measurement and compensation system.

In this paper, the design and analysis of the automatic error compensation of machine tools were studied. An indirect measurement method of the error at the tool center point (TCP) by kinematic modeling of a machine tool was proposed. In this approach, the measurement of six degrees of freedom (DOF) error elements of a linear axis motion is required. In order to achieve the measurement, a dual linear scale system was proposed, and the system requirement was estimated by several preliminary calculations. Based on the design, a physical prototype was developed, and the feasibility was investigated by a series of measurement experiments. By comparing the new measurement system with a conventional measurement method, it was verified that the new system could measure the motion error as expected.

Concept and Composition of the Dynamic Error Compensation System

Concept of the dynamic error compensation system

Among the various errors of machine tools, machine users are mostly concerned with the relative positioning of the TCP with respect to the target point on the work surface because that determines the final dimensional accuracy of the machined workpiece. However, currently, there is no technology to measure the TCP accuracy directly during an actual cutting operation. In order to solve this problem, an approach to identifying the accuracy indirectly by using a kinematic model of machine tool was proposed.

Indirect TCP error measurement with a kinematic model of a machine tool

A typical three-dimensional machine tool motion can be achieved by linking three mutually orthogonal linear axis components, which are generally called X-, Y-, and Z-axis. The errors in each linear axis motion are linked along with the structure of the machine, resulting in the relative displacement between the TCP and the target point on the workpiece. The kinematic model is a mathematical tool to describe how the errors in each axis are linked together and propagate to the error at the TCP [10]. The advantage of this method is that the error at the TCP

can be mathematically derived even if a direct measurement of the error is impossible, by knowing the errors of each linear axis instead.

The errors of a linear axis are defined with six degrees of freedom (DOF) error elements [12]. Fig. 1. shows the error elements of the X-axis. With these error elements, a so-called homogeneous transformation matrix (HTM) is composed. For example, the HTM of the X-axis is defined as

$$\mathbf{H}_X \equiv \begin{bmatrix} 1 & -E_{CX} & E_{BX} & x + E_{XX} \\ E_{CX} & 1 & -E_{AX} & E_{YX} \\ -E_{BX} & E_{AX} & 1 & E_{ZX} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

For the error of the Y- and Z-axis, $\mathbf{H}_Y$ and $\mathbf{H}_Z$ can be defined in the same way. By using the matrices, the error at the TCP can be derived by multiplying the errors in the axis configuration of the machine. For example, the axis configuration of a horizontal machine tool is expressed as [w B Z b X Y t], as shown in Fig. 2, with the notation defined in the ISO standard [12]. Then, the error at the TCP $\mathbf{e} = [e_x, e_y, e_z, 1]^T \in \mathbb{R}^{4 \times 1}$ can be derived by linking the HTMs, as follows:

$$\mathbf{e} = \mathbf{H}_Z \cdot \mathbf{H}_X \cdot \mathbf{H}_Y \cdot \mathbf{t} - \mathbf{w} \quad (2)$$

where e_x , e_y , and e_z are scalar values that represent the TCP deviation from its ideal position; $\mathbf{t} = [x_t, y_t, z_t, 1]^T \in \mathbb{R}^{4 \times 1}$ is the coordinate of the TCP in the spindle coordinate system, which is locally defined on the Y-axis component; and $\mathbf{w} = [x_w, y_w, z_w, 1]^T \in \mathbb{R}^{4 \times 1}$ is the position vector of the TCP in the workpiece coordinate system. Thus, the error at the TCP can be indirectly measured by measuring the six DOF error elements of each linear axis.

Several technologies for the measurement of the errors of a linear axis motion are reported. For example, multi-DOF measurement systems based on laser interferometry [13], quadrant photodiodes [14], or inertial measurement units [15] were developed. Therefore, even though there is no direct measurement method for the TCP accuracy, there are various types of measurement methods for linear axis motion errors. Based on this idea, by installing an appropriate sensor system on a machine to measure the linear axis error, the TCP error can be identified indirectly with the kinematic model.

Selection of sensors

In order to realize the measurement of the six DOF error elements, appropriate sensors should be chosen. Sensors with satisfactory accuracy performance are generally expensive and can break easily in such a harsh environment as a machining process. Therefore, the selection of a sensor is a challenging task. The candidate sensors were listed, and their features were compared, as shown in Table 1.

Among the multiple options, an advantageous feature of linear scales was focused on. Linear scales are commonly used in modern CNC machine tools for position feedback control, so they are already used as a built-in sensor. Although a single linear scale can measure only the position of a single axis, by using two linear scales in parallel for one axis, angular error measurement becomes possible, as shown in Fig. 3. Recently, linear scale technology has grown rapidly, and the measurement of multiple DOF has become possible in principle [16].

From this perspective, the fundamental elements of design to develop a linear-scale-based measurement system were studied.

Design of a dual linear scale system for yaw error measurement

The principle of yaw measurement is explained using the illustration in Fig. 3. Suppose that a moving component moves along the X-axis. Two linear scales are installed on both sides of the moving component. Let us label the scales as scale X_1 and X_2 to distinguish them from each other. First, the moving component is located at a start position, which is the origin of the measurement. At this point, the position and errors of the component are regarded as zero. Next, the

component is moved to a target point, and let A and B denote the position readings on the scales X_1 and X_2 , respectively. Then, the yaw angular error E_{CX} can be calculated by the following equation:

$$E_{CX} = \tan^{-1} \left[\frac{x_2 - x_1}{D_X} \right] \approx \frac{x_2 - x_1}{D_X} \quad (3)$$

Here, the approximation $\tan^{-1}\theta \approx \theta$ can be done because generally the relative position difference $x_2 - x_1$ is on the order of micrometers, whereas the distance D_X between the paired linear scales indicated in Fig. 3 is on the order of meters.

Synchronous data capturing

In order to measure the yaw angle based on this principle, the position data must be synchronized to obtain an accurate result since the error calculation is done with a digital or discrete sampling system. The required time accuracy of this synchronization was assessed by the following calculation.

Assume that a moving component moves along the X-axis at a feed speed of F mm/min. The scale X_1 is sampling the position at a sampling interval of t seconds, while the sampling of the scale X_2 has a time misalignment with respect to X_1 of Δt seconds; i.e., the sampling of the scale X_2 takes place every $t + \Delta t$. Then, the position readings of X_1 and X_2 are $x_1 = Ft$ and $x_2 = F(t + \Delta t)$. The angular measurement error ΔE_{CX} of the moving component is calculated as

$$\Delta E_{CX} \approx \frac{x_2 - x_1}{D_X} = \frac{F\Delta t}{D_X} \quad (4)$$

In this study, synchronization is achieved by controlling the timing of the data acquisition of the read heads with the following principle.

The device that captures the synchronous data distributes a clock signal to the read heads, as illustrated in Fig. 4 (a). In the figure, only one read head is shown for the explanation, but the same signal communication takes place for the other read heads as well. Suppose that the digital circuits in the systems are designed in such a way that the signal communications between the read head and the data-capturing device take place at the rising edge of the clock signal. The data-capturing device sends a request signal to the output interface in the read head at a certain rising edge of the clock, as indicated with the green arrow in Fig. 4 (a).

Once the read head has received the request signal, as shown in Fig. 4 (b), the read head reads the current position signal on the linear scale and sends the position data back to the capturing device at the next rising edge of the clock. By distributing the same clock signal to all the read heads, the above signal communication is executed with the same timing. Thus, the position data from multiple linear scales can be obtained at the same time.

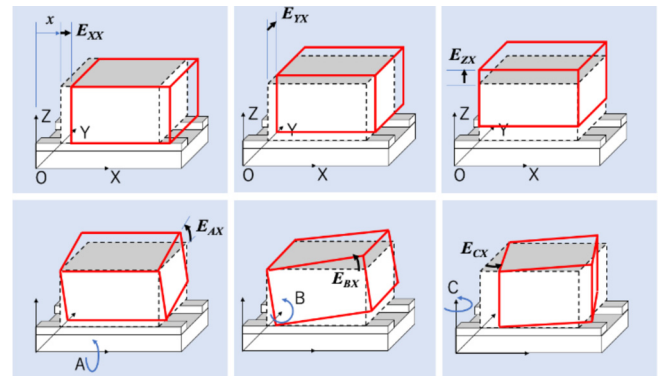


Fig. 1. The 6 DOF error elements of the X-axis.

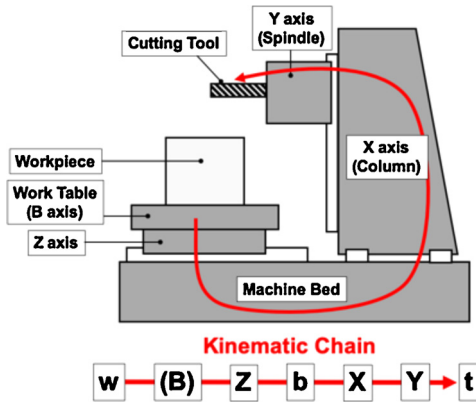


Fig. 2. The axis configuration of a horizontal machine tool.

Table 1
Comparison of sensors.

Sensor	Resolution	Uncertainty	Unit price
Clinometer	0.1 μ rad	1 μ rad	\$5,000
Autocollimator	0.0005 μ rad	0.5 μ rad	\$30,000
Laser interferometer	0.03 μ rad	$\pm 0.6\% \pm (0.5 + 0.1L)$	\$20,000
Linear scale (dual use)	$\frac{0.01}{D} \mu$ rad	$\frac{1.5 + 1.5L}{D} \mu$ rad	\$2,000

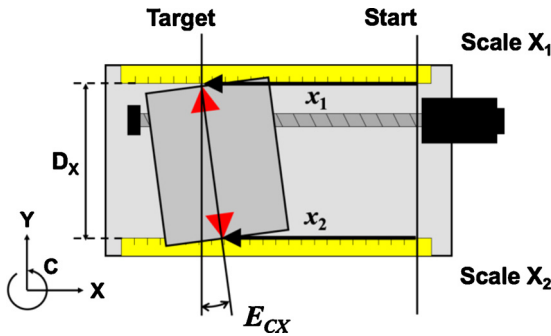
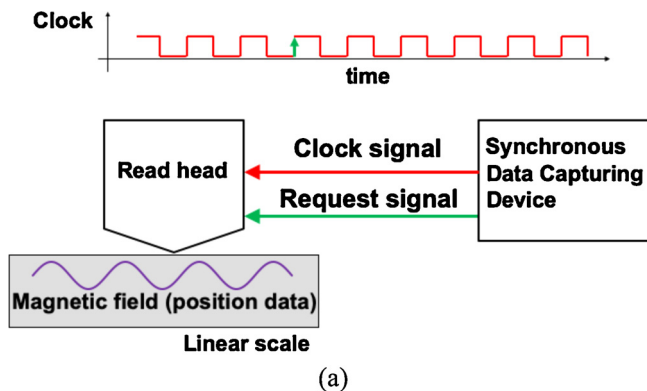
Fig. 3. The measurement principle of yaw angular error E_{CX} with two linear scales.

Fig. 4. Synchronous data capturing by using a clock signal.

Data postprocessing

In machine tool error analysis, the repeatability of motion is evaluated from data obtained by iterative measurement. For motion with repeatability, the measured raw data are regarded as a combination of two elements: systematic and random elements of the error data.

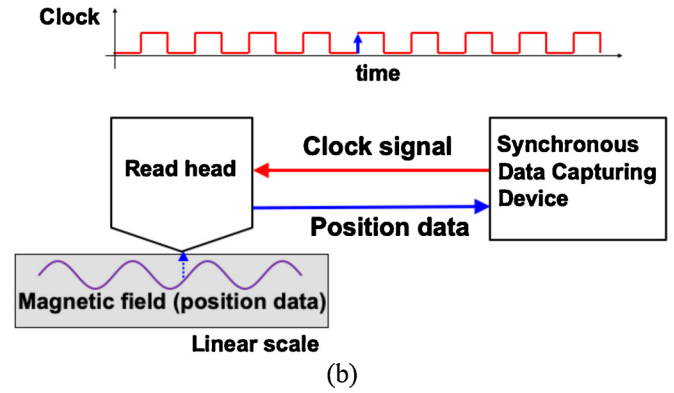


Fig. 4. (continued)

Systematic error is the reproducible and predictable part of the data set and thus regarded to represent the repeating motion of the machine. Random error is the variance of the data points, which is typically due to the signal noise of the measurement, small vibrations of machine components, or any other disturbance in the motion or the measurement. Therefore, in order to determine the dynamic change in the repeatability, this systematic error should be extracted from the data points and compared.

Fig. 5 is an example of yaw angle data measured in this study. All data points sampled at position $Y = -280$ mm with a sampling rate of 100 Hz in five iterative measurement cycles were overlaid in one figure to visualize the repeatability. As can be seen, the measured yaw values are distributed within a specific range. Fig. 6 is the histogram of the data. The histogram implies that the measurement values are subject to a specific probabilistic distribution. In this study, as typically done in machine tool error analysis, the data distribution is treated as a normal distribution. Then, the mean value represents the systematic error, and the variance of the distribution represents the random error.

Let $E_{ir}^{(t)}$ denote the raw data of yaw sampled at position i and time t , where $r = 1, \dots, m$ is the index of the data point. Then, the systematic error $\bar{E}_i^{(t)}$ can be calculated by

$$\bar{E}_i^{(t)} = \frac{\sum_{r=1}^m E_{ir}^{(t)}}{m + 1} \quad (5)$$

The dynamic change in yaw can be determined by comparing the $\bar{E}_i$ obtained at a certain time interval between t_1 and t_2 .

$$\Delta \bar{E}_i = \bar{E}_i^{(t_1)} - \bar{E}_i^{(t_2)} \quad (6)$$

Plug this into the HTM, and the dynamic change in the TCP position can be derived from the kinematic model. Then, by updating the position command, the dynamic change can be canceled out. The detailed procedure is explained in Section 4.2.1.

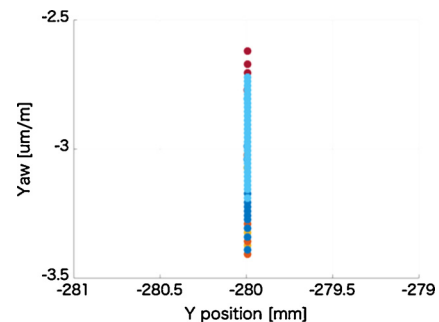


Fig. 5. Synchronous data capturing by using a clock signal.

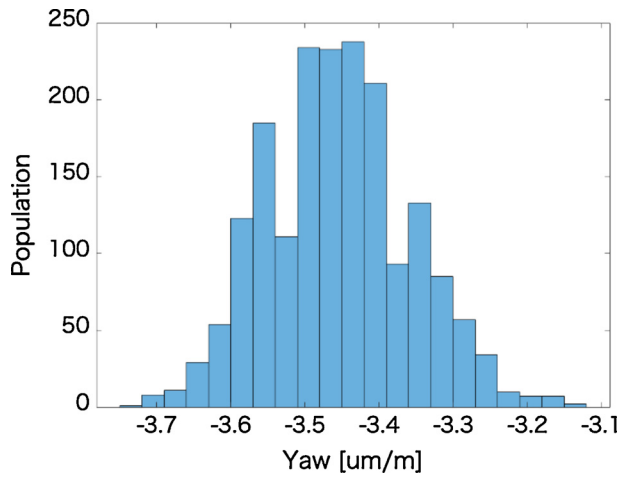


Fig. 6. The histogram of the yaw.

Prototype System for a Verification Study

In order to investigate the effectiveness of the error measurement and compensation method, a physical prototype was required for experimentation. In this section, the hardware employed to construct the prototype machine is introduced.

Hardware

CNC machine tool

For this study, a medium-sized horizontal machining center, NHX4000 2nd Generation designed by DMG MORI Co., Ltd., is chosen. Fig. 7 is the exterior view and the axis configuration of the machine [17].

Linear scale

The linear scale plays a vital role in this system as the internal sensor to collect the machine's position data, which are necessary to calculate the angular error of the moving component. In this study, SmartSCALE, a production of Magnescale Co., Ltd., was chosen to develop a prototype system. Fig. 8 shows an exterior view of a SmartSCALE. SmartSCALE Type SQ57 is an absolute type magnetic linear scale, and Table 2 summarizes its specification.

Scale-data-capturing device

As discussed in Section 2.5, in order to measure the angle based on the principle, a synchronous data-capturing system is required to obtain the position data of multiple linear scales at the same moment. For this study, a data-capturing device BD200 shown in Fig. 9 was also developed by Magnescale.

The linear scales and BD200 are synchronized with a 40 MHz clock signal. By communicating in accordance with this clock signal, all the read heads can send the position data to BD200 at the same moment.

Based on equation (4), the measurement error of yaw angular deviation due to time misalignment is estimated. The specified time misalignment Δt of BD200 is 5 ns. For NHX4000, the maximum feed speed F of the linear axes is 60 m/min. Then, the maximum yaw measurement error δE_{YAW} due to this misalignment can be

$$\delta E_{YAW} \leq \frac{60 \frac{m}{min} \cdot 5 ns}{D} = \frac{5 nm}{D} = 0.021 \mu m/m \text{ (X-axis)} \quad 0.008 \mu m/m \text{ (Y-axis)} \quad 0.006 \mu m/m \text{ (Z-axis)} \quad (7)$$

Based on the kinematic model, the measurement errors of the TCP position due to this time misalignment are 0.016 μm (X-axis), 0.004 μm (Y-axis), and 0.003 μm (Z-axis). As the measurement target of this system is errors on the order of micrometers, this data-capturing system

is capable of capturing the scale position data with sufficient time accuracy.

Composition of the system

The linear scales and the data-capturing device are installed on NHX4000. Fig. 10 illustrates the structure of the dynamic error measurement system. Six linear scales are installed at the positions indicated with red bars. The read heads of the linear scales are connected to the synchronous data-capturing system. The captured data are exported to a PC in CSV file format for postprocessing.

Experiments and Results

Proof of concept

At first, the proof of concept of this measurement system was done. The yaw error was measured by two different methods at the same time: a laser interferometer and the linear scale system. The measurement of the scale system was validated by comparing it with the measurement of the laser interferometer, whose accuracy is assured by calibration. Fig. 11 shows a conceptual image of the experiment.

Experimental setup and procedure

For the verification measurement, XM60, a multi-axis laser measurement system produced by Renishaw, is used. XM60 is capable of measuring the six DOF error elements simultaneously by using four parallel laser beams, as shown in Fig. 12. The measurements are realized by a laser launcher that is mounted on the workpiece table and a reflector that is attached to the spindle. The detailed performance specifications are summarized in Table 3.

In the measurement process, the machine is moved through a set of measurement positions that encompass the entire length of the measurement axis. The measurement positions are set at evenly separated intervals. At each measurement position, the machine stops for a few seconds, and the measurement system measures the associated yaw angle. For example, suppose that the Y-axis is measured. Let y_i denote the Y-axis coordinate of the i th measurement position, where $i = 0, 1, 2, \dots$ denotes the order of the measurement position, with the 0th position representing the start position.

At the 0th measurement point, the yaw is set to zero. The yaw error at the i th measurement position is obtained as the relative change from the 0th point. The measurement setup on the test machine is shown in Fig. 13. The measurement was repeated five times, and their arithmetic mean was recorded as a result.

Result and discussion

Fig. 14 shows a comparison of the yaw measurement result. In the

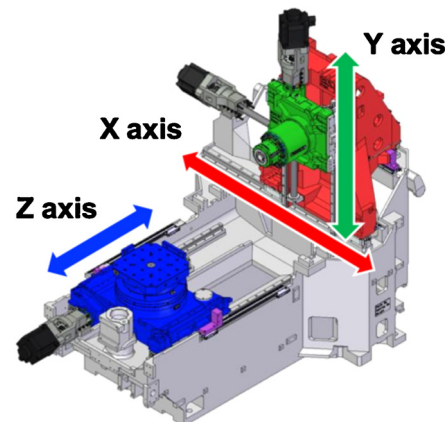


Fig. 7. The exterior and the axis configuration of NHX 4000 by DMG Mori Co., Ltd. [17].

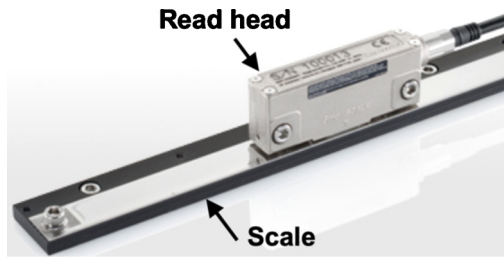


Fig. 8. SmartSCALE by Magnescale Co., Ltd. [18].

Table 2
Specification of the SmartSCALE Type SQ57 [18].

Accuracy	1.5 + 1.5L μ m
Resolution	10 nm
Coef. of thermal expansion	12 μ m/m · K
Waterproof	IP67

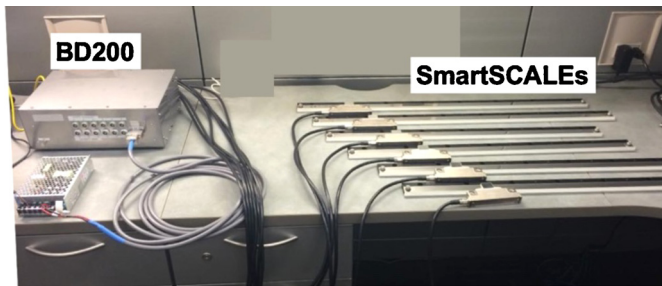


Fig. 9. BD200 connected with SmartSCALES.

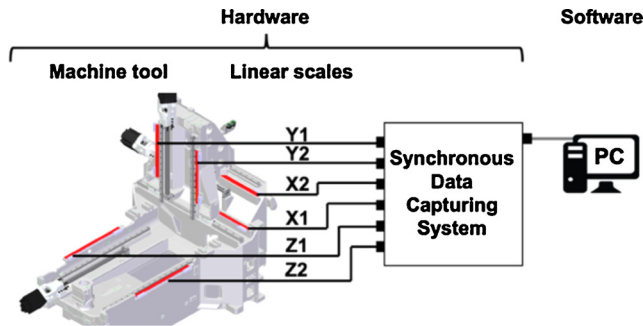


Fig. 10. The composition of the error measurement system.

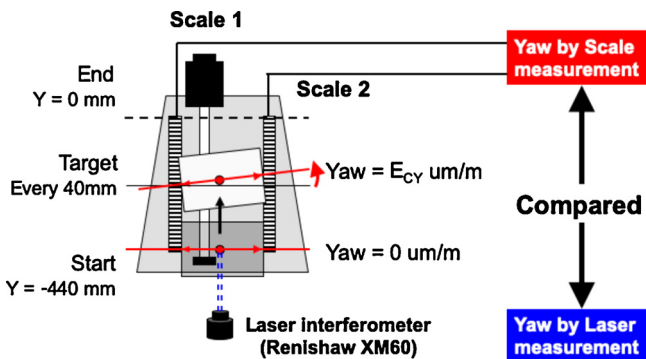


Fig. 11. The verification of the yaw measurement principle by comparing the measurement with a laser measurement.

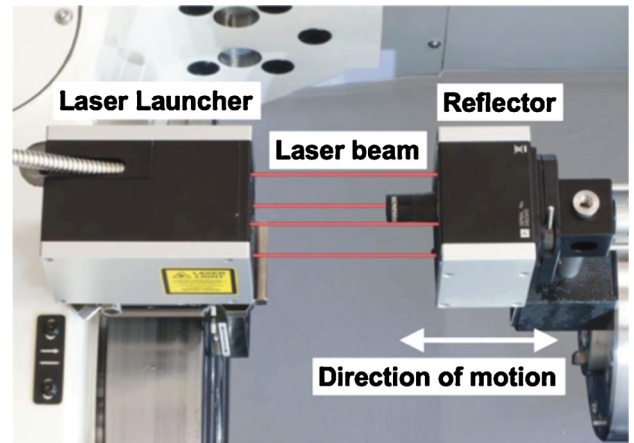


Fig. 12. XM60 laser measurement system [19].

Table 3
Specification of XM60 [17].

Linear	Accuracy	± 0.5 ppm
	Resolution	1 nm
	Range	0 to 4 m
Angular (Yaw)	Accuracy	$\pm 0.006 A \pm (0.5 \mu\text{rad} + 0.1 L \mu\text{rad})$ (A = displayed angular reading) (L = measured distance in meters)
	Resolution	0.25 μ rad
	Range	250 μ m radius

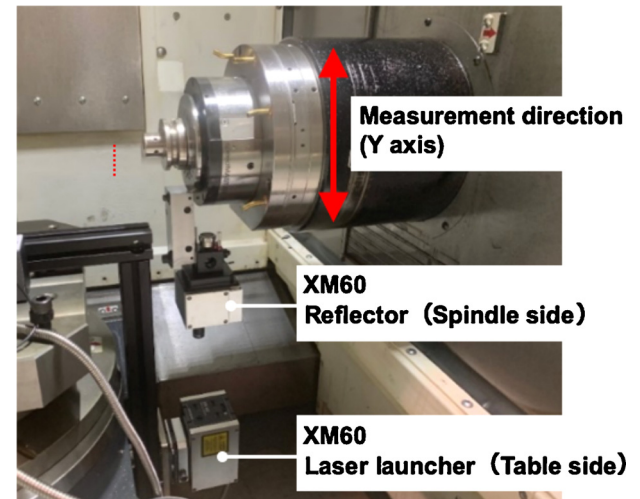


Fig. 13. Setup for the Y-axis measurement.

figure, the horizontal axis is the Y-coordinate of the measurement position, and the vertical axis is the yaw angle of the Y-axis component. The measurement value of the linear scale system is plotted in red, and the result of the XM60 is plotted in blue.

The red shaded zone indicates the uncertainty of the linear scale system estimated as follows. There are primarily four contributors to the overall measurement uncertainty of the scale system: linear scale accuracy, noise in the position signal, the parallelism of the paired scales, and time misalignment of the data sampling. They might be included in the measurement result, but they cannot be identified individually with this measurement. Therefore, they are treated as uncertainty in the measurement. The overall uncertainty is estimated by the Type B evaluation as:

$$U_C = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2} \quad (8)$$

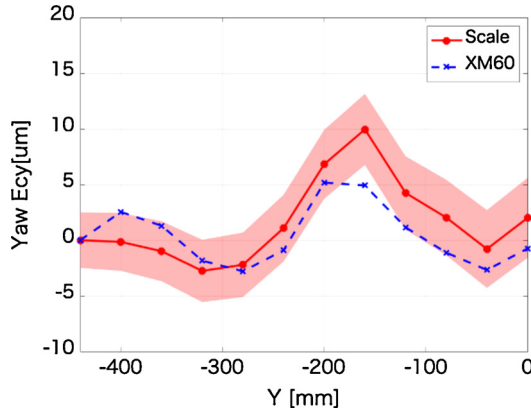


Fig. 14. Comparison of the measurement value of the linear scale system and that of XM60.

Table 4
Uncertainty of the measurement of the scale system.

Contributor	Symbol	Standard uncertainty	Sensitivity coefficient
Linear scale accuracy	σ_1	$1.5 + 1.5L \mu\text{m}$	1/D
Signal noise	σ_2	$0.08 \mu\text{m}$	1/D
Parallelism of the paired scales	σ_3	$\frac{L}{\cos 0.61 \times 10^{-3}} - L \mu\text{m}$	1/D
Time misalignment of the data capture	σ_4	$0.005 \mu\text{m}$	1/D
Combined standard uncertainty	U_C	$\frac{1.5 + 1.5L}{D} \mu\text{m/m}$	-

(L = measured distance in meters)

(D = distance between the paired scales. D = 0.6 m for the Y-axis)

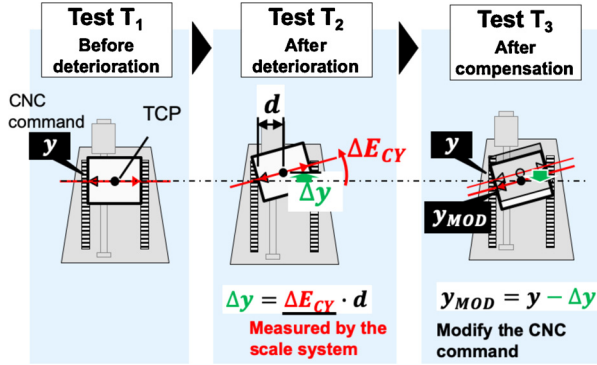


Fig. 15. Detection and compensation of TCP accuracy deterioration by using the scale measurement system.

The values are summarized in Table 4. The combined standard uncertainty is indicated as the red shaded zone in Fig. 14. As can be seen, the measurement of the scale system agreed with that of XM60 within the uncertainty boundary at 11 out of 12 measurement points except for one point at Y = -160 mm. This result indicates that the scale system can measure the yaw error based on the measurement principle of the dual scale.

Detection and compensation of accuracy deterioration

In the previous section, it is shown that the scale system can measure the yaw angular deviation of the machine component based on the proposed measurement principle. The next test is to investigate the feasibility of the system for detection and compensation of the accuracy deterioration. In the test, a situation was assumed in which the machine accuracy deteriorated with age, and the detection and compensation for

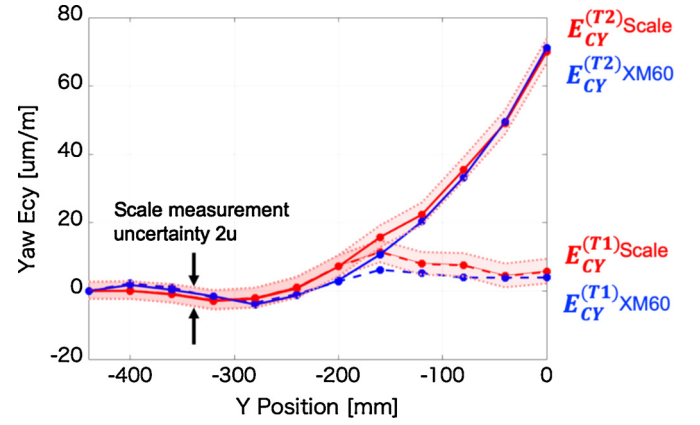


Fig. 16. Comparison of yaw E_{CY} before and after the deterioration.

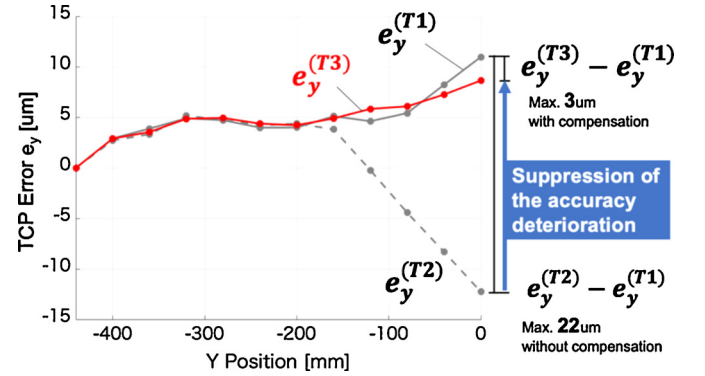


Fig. 17. Reduction of the TCP positioning error after the error compensation.

the deterioration were attempted by this system. The deterioration was replicated for the purpose of the experiment by intentionally distorting the linear guideways. By comparing the yaw before and after the deterioration, the deterioration of yaw can be determined, and its associated positioning accuracy deterioration at the TCP can be calculated by the kinematic model. The detected accuracy deterioration is compensated by modifying the machine motion.

Experimental setup and procedure

Three measurement tests verify the effectiveness of the detection and compensation of the accuracy change. Let T_1 , T_2 , and T_3 indicate the test before the deterioration, after the deterioration, and after the compensation, respectively.

i) Test T_1 : measurement before the deterioration

At T_1 , the yaw and the positioning accuracy before the deterioration are measured by the linear scale system.

ii) Test T_2 : measurement after the deterioration

After T_1 , the linear guideways are distorted, and the measurement test T_2 of the yaw and the positioning accuracy is done. Let $\bar{E}_{CY}^{(T1)}$ and $\bar{E}_{CY}^{(T2)}$ denote the yaw value measured at T_1 and T_2 , respectively. Then, the accuracy deterioration $\Delta \bar{E}_{CY}$ is calculated as:

$$\Delta \bar{E}_{CY} = \bar{E}_{CY}^{(T2)} - \bar{E}_{CY}^{(T1)} \quad (9)$$

Then, using the kinematic model, the TCP accuracy is calculated as:

$$\begin{bmatrix} 0 \\ e_y \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & \bar{E}_{CY}^{(T)} & 0 & 0 \\ \bar{E}_{CY}^{(T)} & 1 & 0 & y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} d \\ 0 \\ 0 \\ 1 \end{bmatrix} - \begin{bmatrix} d \\ y \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ \bar{E}_{CY}^{(T)} \cdot d \\ 0 \\ 0 \end{bmatrix} \quad (10)$$

Equation (10) is derived by replacing all error elements except for $\bar{E}_{CY}$ with 0 in equation (2) since only Y-axis motion was considered in

this experiment. Then, the TCP accuracy deterioration Δe can be determined as:

$$\begin{bmatrix} 0 \\ \Delta e_y \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \bar{E}_{CY}^{(T2)} \cdot d \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} 0 \\ \bar{E}_{CY}^{(T1)} \cdot d \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \Delta \bar{E}_{CY} \cdot d \\ 0 \\ 0 \end{bmatrix} \quad (11)$$

In order to compensate the deterioration Δy , one of the most straightforward compensation schemes is used. The scheme is to subtract Δy from the initial CNC command and generate the modified command $y_{MOD} = y - \Delta y$, as shown in Fig. 15.

iii) Test T3: measurement after compensation

With the compensation, the measurement t_3 of the yaw and the positioning accuracy is done. If the compensation is successful, the accuracy deterioration is canceled out, and the positioning accuracy of T_3 should be the same as T_1 .

The test setting is the same as shown in Fig. 13. The verification measurement by XM60 was done in the three tests. In addition to the yaw change $\Delta \bar{E}_{CY}$, the TCP positioning accuracy change Δy was also measured. As XM60 can measure the two error elements at the same time, the measurement data are used.

Result and discussion

The measurement result is shown in Fig. 16. The graph shows the relative change in yaw induced by the distortion of the guideways for the yaw before the distortion. As can be seen, the change measured by the scale system agreed well with the change measured by XM60. This agreement indicates that the scale system can detect the change in yaw as accurately as XM60.

Based on this result, compensation was performed with dynamic compensation. Fig. 17 shows the result. The positioning accuracy change relative to the initial condition was compared with and without the compensation. The positioning accuracy change without the compensation is shown with red bars, and the accuracy change with the compensation is shown with blue bars. Without the compensation, the accuracy deterioration was up to approximately 22 μm at $Y = 0 \text{ mm}$. On the other hand, with compensation, the deterioration was reduced to approximately 3 μm . This result shows that the dynamic measurement and compensation system successfully compensated for the positioning accuracy deterioration.

Conclusion

In this paper, the design and analysis of the automatic error compensation of machine tools were studied. In order to achieve the measurement, a dual linear scale system was proposed, and the system requirement was estimated by several preliminary calculations. Based on the design, a physical prototype was developed, and the feasibility was investigated by a series of measurement experiments. By comparing the new measurement system with a conventional measurement method, it was verified that the new system could measure the motion error as expected.

In order to verify the concept, the measurement performance of the

scale system was assessed by using a laser interferometer. As a result, the measurement value of the scale system agreed with the measurement value of XM60 within the uncertainty estimated at the design stage.

In order to investigate the feasibility of the system for detection and compensation of the accuracy deterioration, the yaw measurement was performed for two different yaw accuracy conditions. The scale measurement of the yaw agreed with the verification measurement of the laser within the designed uncertainty. This indicates the scale system could detect the deterioration of the yaw.

Based on the accuracy deterioration detected by the scale system, the compensation of the accuracy deterioration was attempted. With the compensation, the maximum accuracy deterioration was successfully suppressed from 22 to 3 μm , which is verified by the laser measurement. This indicates that the accuracy of a machine tool can be maintained by the dynamic measurement and compensation system.

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