NEW DEVICE FOR RAPID MEASUREMENT OF MACHINE TOOL GEOMETRIC ERRORS

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DOI: 10.17973/MMSJ.2022_10_2022120

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Control systems of modern machine tools are equipped with a number of functions for volumetric accuracy enhancement. These functions can compensate for all the geometric errors of the axes, which are characterized by 21 errors for a 3-axis machine tool. Compensation data are stored in compensation tables and the control system calculates actual compensation based on these tables and actual machine tool position. Geometric errors are measured within the machine tool maintenance plan and it presents a time-consuming process. Measurement is mainly based on interferometric devices, where the precise setup of laser source and detector is challenging. This article introduces an original system for automatic interferometer set up to speed up the measurement of geometric errors. The system is designed for the interferometer Renishaw XM-60, which simultaneously measures all 6 degrees of freedom. The developed control software identifies interferometer position and transforms the measured data into a machine coordinate system. Numerical simulation verified the proposed solution.

KEYWORDS

volumetric accuracy, geometric errors, interferometric measurement, Renishaw XM-60, compensation tables

1 INTRODUCTION

Volumetric accuracy represents the production quality of a machine tool. It is caused by a variety of factors at the manufacturing stage and can be improved by a software compensation of axes geometric errors. Thus, the measurement of geometric errors is essential for improving the overall accuracy of a machine tool.

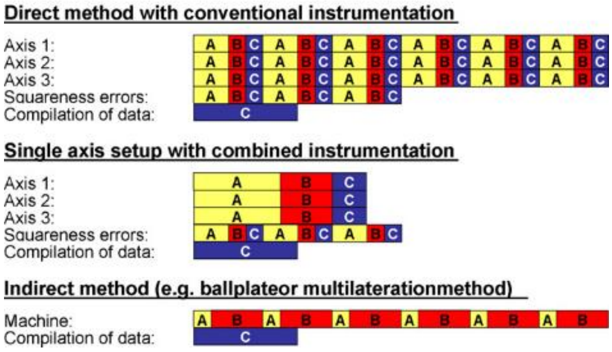

Figure 1. Comparison of measurement methods with respect to time consumption. Setup phase is denoted by A, data acquisition by B and evaluation phase by C [Schwenke 2008].

As [Satori 1995] states, the time required for the measurement of geometric errors was the major constraint for employing compensation techniques at a wider scale. This statement is confirmed in the Fig. 1, where different measurement methods for a 3-axis machine are compared.

Direct methods allow the measurement of a single machine axis without the involvement of other axes [Schwenke 2008]. A typical conventional instrument for this method is a laser interferometer. The instrumentation must be set up for measuring of every error component. For instance, a 3-axis machine tool requires the acquisition of twenty-one error components: six error components for each axis and three squareness errors [Holub 2016]. Thus, the time required for the acquisition of geometric errors using conventional instrumentation is significant and most of the time is consumed within device setup phase.

Combined instrumentation allows the measurement of all six error components of an individual axis simultaneously. For example, the multi-axis calibrator Renishaw XM-60 (shown in Fig. 2) incorporates three laser beams plus an LED beam to measure linear, straightness and angular errors simultaneously [Renishaw 2021]. This significantly reduces the number of required setups. Namely, only six setups are necessary for the acquisition of geometric errors of a 3-axis machine compared to twenty-one with conventional methods. However, as can be seen in Fig. 1, each setup requires more time due to increased complexity.

Figure 2. Mult- axis calibrator Renishaw XM-60 consists of a launch unit (right) and a receiver unit (left) [Renishaw 2021].

Indirect methods implement a multi-axis motion for the identification of geometric errors [Schwenke 2008]. They can be either based on the measurement of an artefact or use so-called contour measurements [Schwenke 2008]. The most notable example of this group is a LaserTRACER developed and manufactured by Hexagon AICON ETALON GmbH (Fig. 3). According to [Schneider 2004], its principle is based on the measurement of relative distance change between reference points fixed to the base and points fixed to the tool center point. Errors of the machine can be obtained from the differences between the measured and the nominal distance changes. The aforementioned principle is similar to multilateration used in GPS with the difference that distance change is obtained directly from the interferometer. Hexagon [Hexagon 2021] distinguishes two types of multilateration: real-time and sequential. Real-time multilateration uses four LaserTRACERs while sequential uses only one that is manually relocated to different positions. For commercial purposes, sequential multilateration provides sufficient accuracy and is widely used for machine tool calibration [Hexagon 2021].

The most common method for geometric accuracy measurement is using an interferometer. The biggest disadvantage of an interferometer is the setup time because the laser beam has to be perfectly aligned with the machine tool's axis. Moreover, the alignment has to be repeated for every axis. This drawback is especially prominent for large machines. The development of combined instrumentation and indirect methods has allowed reduction of the measurement time significantly [Schwenke 2008], however shortening of setup phase for combined instrumentation would rapidly increase the total measurement effectivity.

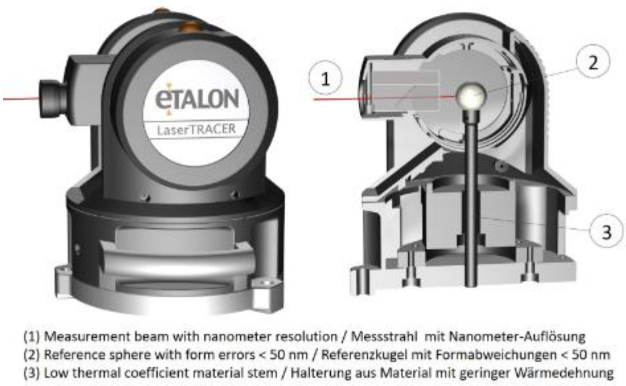

Figure 3. LaserTRACER as a device for indirect geometric error measurement [Etalon 2021].

This article introduces a system of new positioning units for the automatic setup procedure of Renishaw XM-60 with the aim to minimize the time for machine tool axes geometric errors measurement. Position identification of the Renishaw XM-60 is a key element that had to be solved. The position identification algorithm is based on information from the positioning unit sensors and machine tool position. Following the position identification, the trajectories for 3-axis machine tool geometric errors measurement may be calculated. The trajectories consist of 3 lines for main axes and 3 lines for diagonals of X-Y, Y-Z and X-Z axes, where the diagonals yield to axis squareness calculation. The measured data will be used for standard axis geometric compensations, but also for the calculation of the volumetric compensation model. These trajectories may be measured without the proposed system, but the precise alignment of the interferometer is very time-consuming and need to be repeated for each measured line. The resulting system is designed for high speed measurement not only within the regular maintenance but also, for example, before precise machining.

2 GEOMETRIC ERRORS MEASUREMENT SYSTEM

The scheme of the prosed measurement system is shown in Fig. 4. The system consists of control IPC/PLC, launch and receiver positioning units and a Renishaw XM-60 (XM-60) interferometer. The launch unit can be located anywhere in the machine tool working space and the receiver positioning unit is clamped in the machine tool spindle. Based on the identified position of the launch unit, the system will automatically compute the measuring trajectories of the machine. The IPC/PLC communicates with the machine tool control system and XM-60 and it controls the positioning units. Communication with the machine tool control system is mainly intended for machine actual position reading, which is used for initial position identification of the units. Communication with XM-60 operates with actual measured values, where no other software is required for data acquisition (the system is equipped with direct communication with XM-60). Control of position units is used for both manual and automatic positioning and actual position reading.

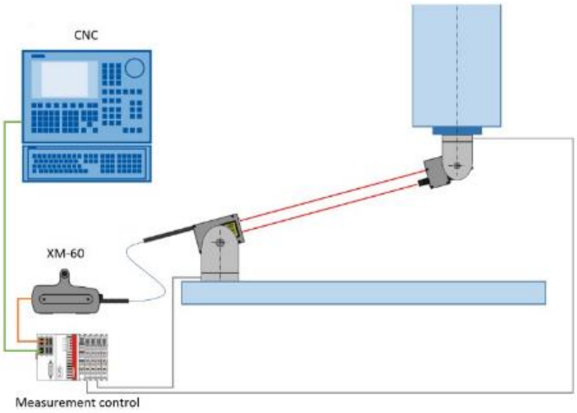

Figure 4. Measurement system concept. The launch unit is fixed in the machine tool workspace and the receiver unit is clamped to the spindle.

Four main tasks of the system can be identified:

1. Preparation of the measurement program.
2. Execution of the measurement program.
3. Identification of axis geometric errors and axes squareness.
4. Generation of compensation tables.

The first task is concerned with the automation of the setup phase and is the main topic of this paper. The conventional approach with combined instrumentation is to manually adjust the measuring device for the identification of each error component. The manual adjustment procedure purpose is to set XM-60 units and find the trajectory of the machine tool axis such that laser beams stay in range throughout the whole measurement. Such a laborious and time-consuming procedure is necessary because the exact positions of XM-60 units are unknown. The designed positioning mechanism aims to simplify this procedure. Using the predefined sequence or randomly selected of measurement points, the position of the XM-60 launch unit can be identified in the working space of the machine tool very quickly. The launch and receiver units must be manually aimed at each other at each measuring point in this stage of measurement. This is sufficient only within the measuring range of the XM-60, the exact alignment is then performed automatically by the positioning units. Knowing the exact position allows the generation of trajectories (NC programs) for the machine tool during measurement such that laser beams are aligned. Repeating the process for each axis or other lines yields the complete measurement program.

The second task performs automatic error identification using the measurement program from above. The XM-60 units are automatically positioned along the measured axis or other achievable line and then locked for eliminating the inaccuracy of the units during measurement. It is ensured here that the machine tool will be within the measuring range of the XM-60. The machine tool moves along the designed trajectory and stops at the measured points. Error information in all 6 degrees of freedom is stored in these points.

The third task uses the acquired errors to determine the machine tool accuracy or volumetric accuracy model. The raw data is processed and the static component of the error associated with the interferometer's alignment inaccuracy is removed. Finally, the compensation tables in syntax specific to CNC control can be generated. The whole measurement system procedure is demonstrated in the flowchart in Fig. 5.

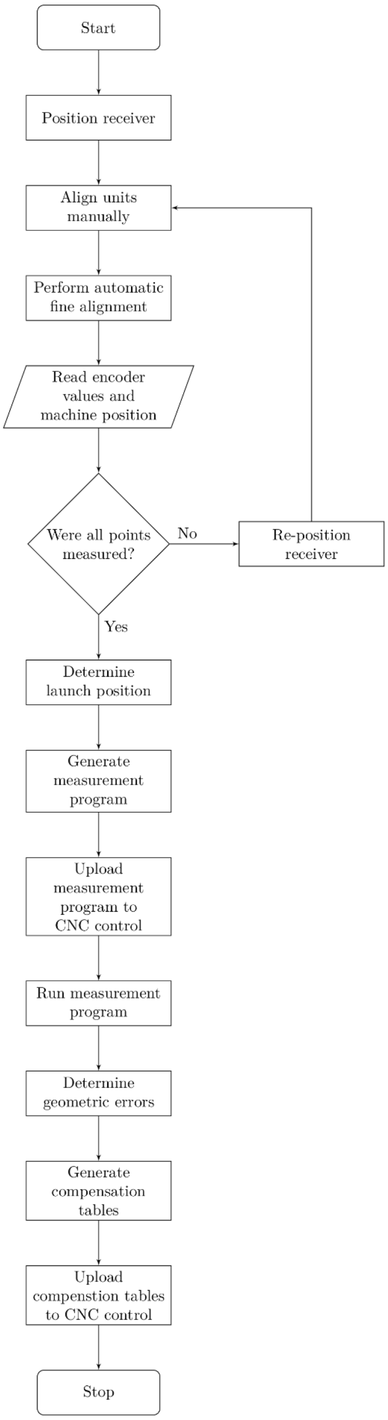

Figure 5. Automatic measurement flowchart for geometric errors measurement (assumption of a tempered measurement system).

2.1 *Design of the positioning units*

The positioning mechanism (shown in Fig. 6) was developed specifically for the XM-60 multi-axis calibrator. The mechanism consists of two units each responsible for positioning the respective part of the XM-60. The launch unit is designed to be placed stationary in the machine's workspace. The receiver unit serves for the positioning of the Renishaw XM-60 receiver part and is designed to be placed in the machine tool spindle, as shown in Fig. 4. The mechanism contains rotary axes only and the kinematic model of both positioning units is shown in Fig. 7. The launch unit consists of two consecutive rotary axes, the receiver unit consists of three consecutive rotary axes. This ensures not only the rotation of the interferometer units relative to each other but also their orientation around the axis of the laser beams.

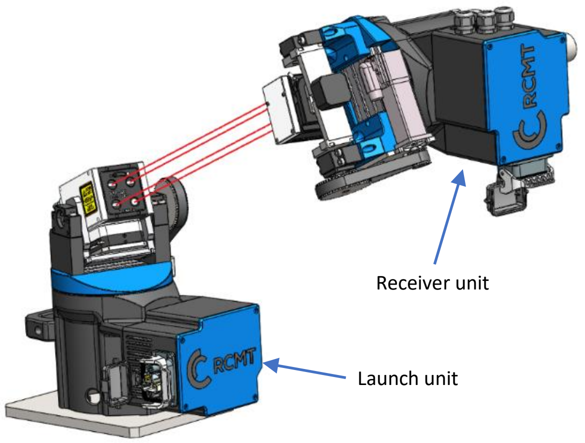

Figure 6. CAD scheme of the positioning units for interferomter Renishaw XM-60.

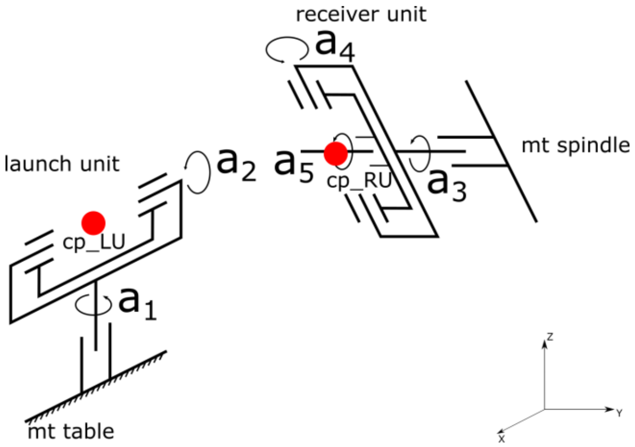

Figure 7. Kinematic model of the launch and receiver units. Red points denote control points of those units and are placed in the intersection of rotational axes.

The basic design of both units is the same. The first rotary axis is integrated into the base of the positioning unit. It is equipped with a servomotor and the rotary drive is transmitted to the rotary head by means of a toothed belt transmission. In addition, the toothed belt is equipped with two tensioning mechanisms to ensure backlash-free movement. The main shaft is mounted in a precision bearing housing, which is connected via an aluminum plate and profiles to the machine table. A detail of the first axis drive is shown in Fig. 8.

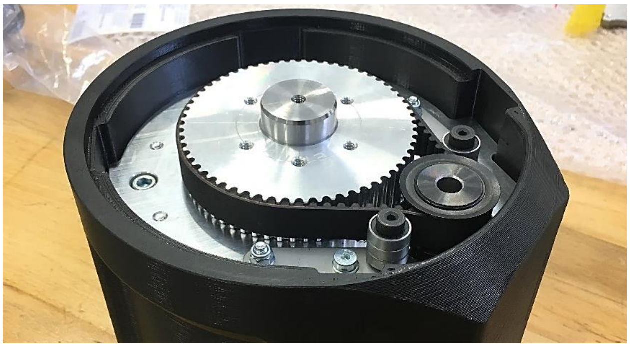

Figure 8. Detail of the first axis drive.

The second axis is designed to tilt the laser head. The axis is again equipped with bearing housings, which are mounted on a supporting aluminum profile. The movement axis is equipped with a servomotor, which is connected to the tilting mechanism via a toothed belt transmission. In the case of the receiver unit, the tilting mechanism is equipped with yet another rotation, which is realized by means of a stepper motor.

The final design of the positioning unit with the interferometer launch unit is shown in Fig. 9. The positioning unit with the receiver part of the interferometer and cone for clamping to the spindle is shown in Fig. 10.

Figure 9. Prototype of the launch unit to be placed in the machine tool working space.

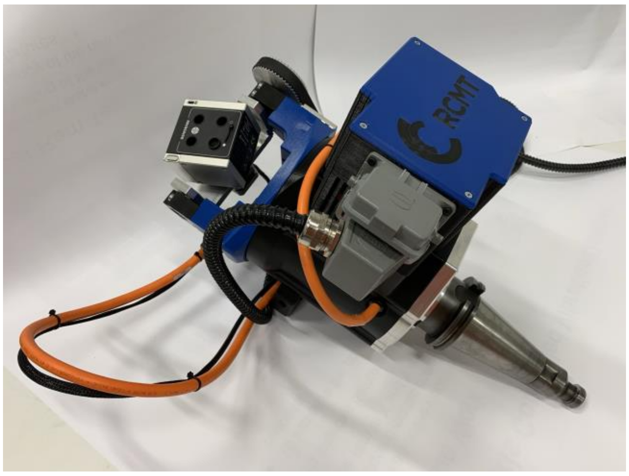

Figure 10. Prototype of the receiver unit to be mounted in the machine tool spindle.

2.2 *Positioning units control system*

The positioning mechanism is controlled by a PC-based controller from Beckhoff. Each axis is driven either by a servomotor or by a stepper motor controlled by a drive. The drives are operated in the cyclic synchronous velocity mode which means the position control loop is solved in the PC-based controller and the other loops (velocity and current control loops) are solved in drives. Essentially, a PC-based controller is responsible for the generation of velocity commands. The wiring scheme of the controller is shown in Fig. 11.

The control system allows two alignment modes - manual and fine automatic alignment. The purpose of manual mode alignment is to find an initial units position, where all the laser beams are in the measurement range. The purpose of automatic fine alignment is to position units such that all the measurements are in the center of the measurement range. Such a configuration means that coordinate systems of the respective units are aligned with respect to each other. The alignment during the whole measurement is achieved using a specifically generated measurement program that incorporates XM-60 units' angular positions as well as machine tool actual position.

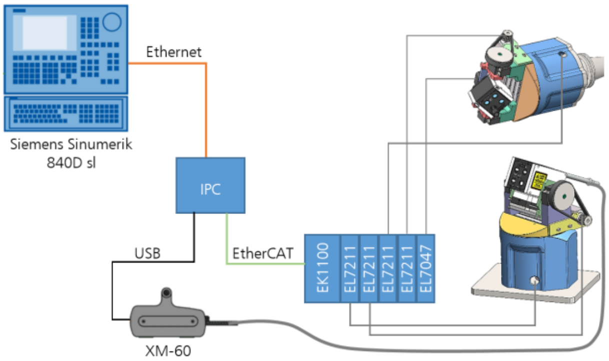

Figure 11. Wiring scheme of the proposed system. Beckhoff EL7211 and EL7047 represent drives for servomotor and stepper motor control, respectively.

From the point of view of control, the alignment is accomplished by modifying the control scheme as shown in Fig. 12. The axes of positioning units are controlled according to the trajectory derived from the measurement program after the alignment. Each axis is extended with an additional position controller that uses feedback directly from the respective channel of XM-60. For units to be aligned all channels except the one responsible for positioning error must show values approaching zero. Thus, the units can be aligned automatically by commanding a setpoint value of zero to the position controllers with direct feedback from XM-60.

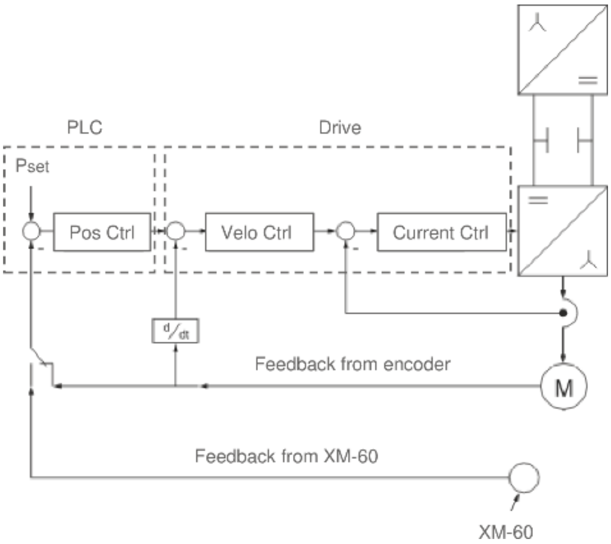

Figure 12. Control scheme of position units axes. The feedback switches between internal encoder and external value from Renishaw XM-60.

2.3 *Position identification*

The aim of the position identification is to determine the precise position of the launch unit. The exact position is essential for machine tool measuring trajectories computation. The calculation is based on multiple alignments of units in different machine tool kinematic configurations where the launch unit is still in the same position in the workspace, only rotations are allowed. Based on the rotation of units axes and machine tool coordinates, the position can be calculated at least in two different ways. The first one considered known launch-receiver units distance, while the second one does not need to measure that distance. Both methods are described in following paragraphs.

2.3.1 Known units distance

This approach is based on closed-loop kinematic chain method [Stejskal 1996], see Fig 13. It follows from the Fig 13 that the interferometer closes the kinematic loop described by the equation

$$\boldsymbol{T}_{MCS\_LU} \cdot [0\;0\;0\;1]^T = \boldsymbol{T}_{MCS\_RU} \cdot [0\;0-l\;1]^T, \tag{1}$$

where $\boldsymbol{T}_{MCS\_LU}$ is the transformation matrix to the launch unit's control point position described in the machine coordinate system (MCS), $\boldsymbol{T}_{MCS\_RU}$ describes the transformation from MCS to receiver unit control point position. Distance between the launch and receiver unit is denoted as l and is the function of the units' positions.

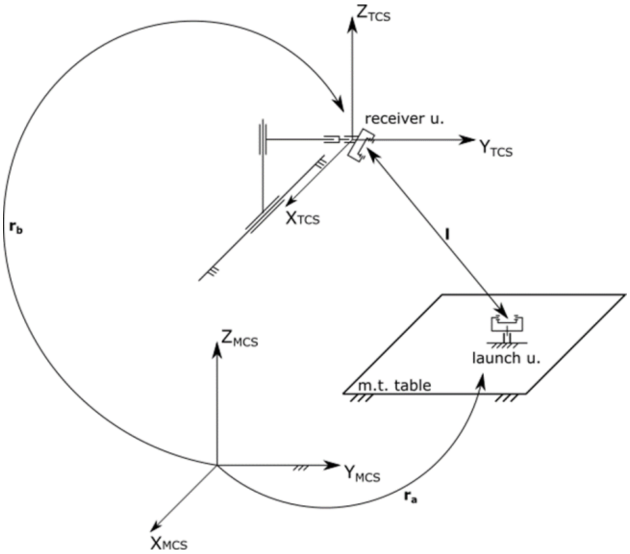

Figure 13. Closed-loop kinematic chain for launch unit position identification

Transformation matrices $\boldsymbol{T}_{MCS\_LU}, \boldsymbol{T}_{MCS\_RU}$ are derived in the form

$$\boldsymbol{T}_{MCS_{LU}} = \boldsymbol{T}_{Z1}(x_{LU})\boldsymbol{T}_{Z2}(y_{LU})\boldsymbol{T}_{Z3}(z_{LU})\boldsymbol{T}_{Z4}(\gamma_{LU})\boldsymbol{T}_{Z5}(\varphi_2)\boldsymbol{T}_{Z6}(\varphi_1), \tag{2}$$

$$\boldsymbol{T}_{MCS_{RU}} = \boldsymbol{T}_{Z1}(x_{RU})\boldsymbol{T}_{Z2}(y_{RU})\boldsymbol{T}_{Z3}(z_{RU})\boldsymbol{T}_{Z4}(\gamma_{RU})\boldsymbol{T}_{Z5}(\varphi_4)\boldsymbol{T}_{Z6}(\varphi_3), \tag{3}$$

where $[x_{LU}, y_{LU}, z_{LU}]$ and $[x_{RU}, y_{RU}, z_{RU}]$ describes the position of control points (cp_LU and cp_RU in Fig. 7) of the launch and the receiver unit, respectively. The angle of launch and receiver unit initial setup is denoted as γ_{LU} (rotation parallel to axis a_1) and γ_{RU} (rotation parallel to axis a_2). Both launch and receiver units are equipped with encoders and actual angles are described as $\varphi_1, \ldots, \varphi_4$ for axes $a_1, \ldots, a_4$. Rotation of axis a_5 is used only for the units' alignment about the laser beam rotation and this angle is not used for position identification. Matrices $\boldsymbol{T}_{Z1}, \ldots, \boldsymbol{T}_{Z6}$ represent basic transformation matrices [Stejskal 1996]. The receiver unit is attached to the tool holder and it is held in the spindle. Its position $[x_{RU}, y_{RU}, z_{RU}]$ is known from the machine tool control system as well as the spindle actual rotation, which describes receiver unit rotation γ_{RU}. The spindle needs to be locked during the measurement and γ_{RU} represents a known constant then. Launch unit position and rotation $[x_{LU}, y_{LU}, z_{LU}]$ and γ_{LU} are unknown variables. The system of equations (1) is of undetermined type with 3 equations for 4 unknowns. However, it can be easily transformed into an over-constrained type by repeating the measurement with the launch unit at multiple locations. These locations are positioned by the machine tool with known coordinates, units' encoders rotation and launch-receiver unit distance. The solution of (1) can be then transformed into residuum minimization:

$$Res = \sum_{i=1}^{n} \left\| \boldsymbol{T}_{MCS_{LU_i}} \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} - \boldsymbol{T}_{MCS_{RU_i}} \cdot \begin{bmatrix} 0 \\ 0 \\ -l_i \\ 1 \end{bmatrix} \right\|_2 \rightarrow min, \tag{4}$$

where n denotes the number of measurement points. Both $\boldsymbol{T}_{MCS\_RU}$ and $\boldsymbol{T}_{MCS\_LU}$ might not be constant since it depends on the machine tool kinematic solution. The system is over-constrained for $n \geq 2$ ($3 \times n$ equations for 4 unknowns). Thus, the unknown variables can be obtained using numerical methods such as the least-squares method. The system of equation (1) is satisfied for the nominal model only without kinematic and rotation errors. Considering the finite accuracy of all encoders and unit kinematic errors, the numerical solution based on residuum minimization (4) is desired. There exists a number of numeric solvers for nonlinear least-squares solution and the solution of system of equations (4) represents a standard numeric task.

2.3.2 Unknown units distance

Since the interferometric measuruement of absolute distance in different positions is not trivial task (in this case, with the Renishaw XM-60, tracking is required to avoid beam loss), alternative method for receiver unit position identification withnout distance measurement was proposed. This method is based on multiple units alignment too, where the receiver unit is in distinct positions and the launch unit position is calculated as the intersection of laser beam vectors, see Fig. 14.

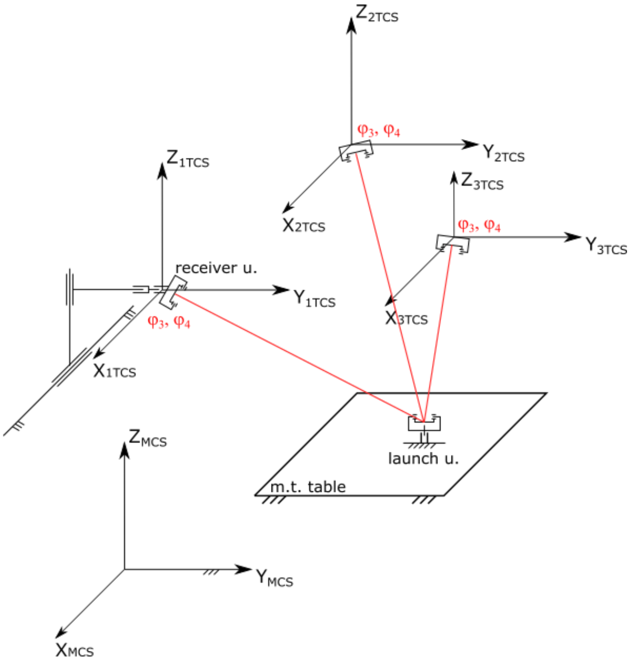

Figure 14. Launch unit position identification with unknown units distance based on laser beam intersection.

The system of equation contains the same 4 unknown $[x_{LU}, y_{LU}, z_{LU}, \gamma_{LU}]$ describing launch unit position. Considering nominal model of the proposed system, there exists unique solution of laser beam vectors intersection. However, the real mechanism is far from ideal one and there will be no exact intersection point and numeric solution is necessary. The proposed solution is based on least-square solution, where a point with minimal distance from all laser beam vectors is calculated. The laser beam vector is computed for every aligned units position in the form of parametric equation of a line

$$\boldsymbol{v} = \boldsymbol{cp\_RU} + t.\boldsymbol{u}, \tag{5}$$

where $\boldsymbol{cp\_RU}$ denotes the receiver unit position, $\boldsymbol{u}$ the laser beam direction and t is the parameter. The launch unit control point $\boldsymbol{cp\_LU}$ is calculated as a point which minimizes the distance from all laser beam lines (5)

$$Res = \sum_{i=1}^{n} |\boldsymbol{v_i}, \boldsymbol{cp\_LU}| \rightarrow min. \tag{6}$$

Based on identified launch unit control point position, the constant initial rotation of launch unit γ_{LU} is calculated as a mean value of difference between rotation φ_1 given by the encoder of axis a_1, and the laser beam direction component related to axis a_1 for aligned launch and receiver units. The mean value is calculated over all measured points to increase the accuracy of γ_{LU} computation.

3 SIMULATION TESTING

Identification of units' position in machine tool workspace is essential for automation of geometric errors measurement. Therefore, a mathematical simulation was performed to verify the proposed identification algorithm. As mentioned before, precise absolute distance measurement using the interferometer is challenging, only the method with unknown units distance was tested. The programming environment MATLAB was used to create a model of a 3-axis machine tool, where the simulation consisted of three different machine tool positions with the launch unit on the table and the receiver unit in the spindle. In these positions, the launch and receiver units were aligned with the aim to get the launch and receiver unit rotations.

Using these data and machine tool coordinates, the launch unit position was identified. There exist a number of algorithms to solve the least-squares problems and MATLAB provides an Optimization Toolbox for solving optimization problems. Since equation (6) represents an overconstrained system of linear equation, the QR decomposition was utilized [Matlab 2021].

3.1 Ideal scenario

Firstly, the simulation was run in an ideal scenario, where the angles of the receiver unit are known exactly and the mechanical structure of the positioning system consider to be nominal. In such a scenario three measurement positions were performed and the position of the launch unit was computed. The results of position identification on simulation data are summarized in Tab. 1. The results clearly validate the suggested method for position identification.

	Launch position		**Receiver position**		
	Set	**Identified**	**1**	**2**	**3**
X [mm]	0	0.0	-1200	0	1200
Y [mm]	1000	1000.0	200	200	200
Z [mm]	1500	1500.0	500	500	500

Table 1. The ideal scenario simulated position identification.

3.2 Scenario with errors

Secondly, the accuracy of the designed and manufactured positioning units was identified and the detected errors were added to the simulation model. The main purpose of the scenario was to evaluate if the proposed device is able to align the XM-60 laser interferometer within the maximum measuring range (4 000 mm) with sufficient accuracy. The rotary axes of the positioning units are blocked during the measurement and it is important to keep the laser beam within the measuring range along the entire stroke of the machine axis. The XM-60 measurement ranges are as follows:

- angular ±500 µrad,
- straightness ±250 µm radius.

The results of tests performed according to this scenario are shown in Tab. 2.

	Launch position		**Receiver position**		
	Set	**Identified**	**1**	**2**	**3**
X [mm]	0	0.08	-1200	0	1200
Y [mm]	1000	1000.01	200	200	200
Z [mm]	1500	1499.96	500	500	500

Table 2. Scenario with errors simulated position identification.

Based on the identification of the position of the launch unit, a simulation testing of the axis straightness measurement was subsequently performed. The XM-60 receiver was placed at a maximum distance (4 000 mm) from the XM-60 launch unit and the units were aligned. Due to an error in position identification the actual position of the launch unit differs from the identified one. Thus, the laser beam is not parallel with the measured axis as demonstrated in Fig. 15 a).

The error bars in the measurement points illustrate the measurement range of the receiver – the laser beam should pass through every bar as is the case for simulated measurement. The dark grey background in Fig. 15 a) marks the range where the

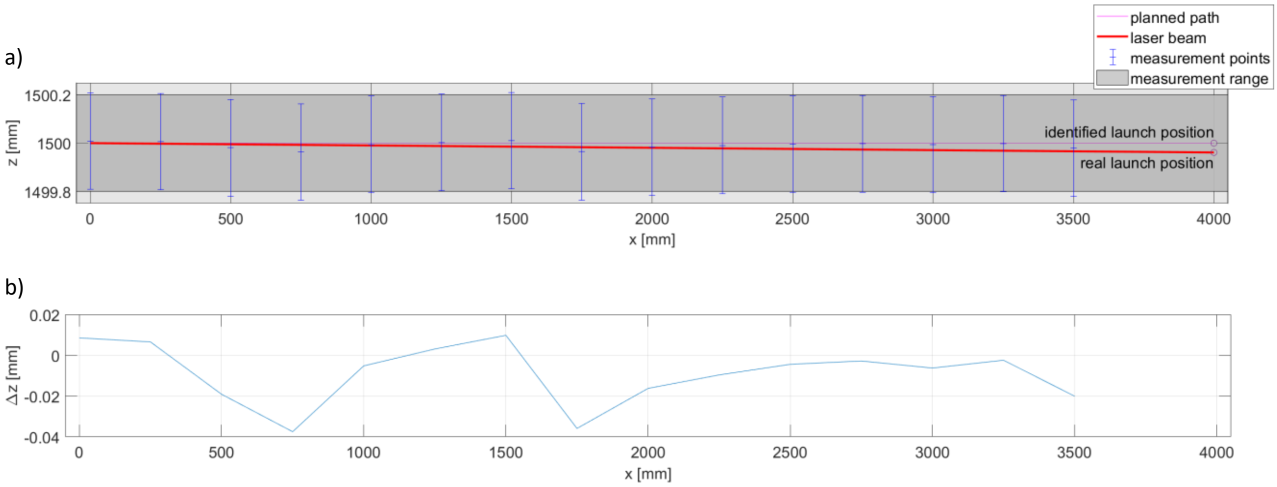

Figure 15. Simulated straightness measurement of X-axis, error in Z direction: a) Laser beam position relative to measured X axis, b) Extracted straightness in the measured points.

receiver unit can be located such that axis error from the range ±50 µm can be measured (light grey).

Because the laser beam is not parallel with the measured axis it is necessary to remove this component from the measurements. The result of the straightness of the measured axis can be seen in Fig. 15 b).

It can be seen from Fig. 15 that the designed positioning units together with the proposed position identification algorithm provide sufficient accuracy for the automated positioning of the laser interferometer XM-60. In the numerical testing, the laser beam was always within the measuring range of the interferometer along the entire stroke of the axis.

4 CONCLUSIONS

A system of new positioning units for the Renishaw XM-60 multi-axis calibrator has been developed to minimize the time required to measure the geometric error of the machine. The system consists of mechanical as well as software components. The mechanical side of the system was manufactured, commissioned and tested to verify functionality and identify achievable accuracy. An algorithm has been developed that will allow the identification of the position of the XM-60 interferometer in the working space of the machine tool. Position identification of the XM-60 is a key element and is based on measuring several discrete machine tool positions. This algorithm was tested by simulation, including the influence of data obtained from real positioning units. At the same time, an algorithm was developed that calculates trajectories and ensures their measurement based on the identified position of the XM-60. It was verified that the designed device together with the proposed algorithm achieves sufficient accuracy and allows automated measurement of the error of individual axes of the machine tool and also its diagonals.

Future work will focus on industrial testing of the proposed system and the use of measured data to calculate the volumetric accuracy of the machine tool. Thanks to automated measurement, it will be possible to obtain the volumetric error of the machine tool in a short time and use it to recalibrate the machine tool before selected machining operations or to research the effect of temperature behavior on the volumetric accuracy.

ACKNOWLEDGMENTS

Funding support from the Czech Ministry of Education, Youth and Sports under the project CZ.02.1.01/0.0/0.0/16_026/0008404 “Machine Tools and Precision Engineering” financed by the OP RDE (ERDF). The project is also co-financed by the European Union.

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