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FROM THE TRADITIONAL MULTILATERATION TO THE INTEGRATED MULTILATERATION APPROACH: A ROADMAP TOWARDS THE AUTOMATIZATION OF VOLUMETRIC ERROR MAPPING PROCESS FOR LARGE MACHINE TOOLS

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Abstract
Multilateration-based volumetric error mapping is gaining widespread adoption in the coordinate measurement machine and machine tool industry as the most effective approach for geometric characterization of large-size machines. In the traditional method, tracking interferometers are placed on the machine table while the measurement retro-reflector moves with the spindle. However, this approach has several limitations, including manual instrument manipulation and a sequential measurement scheme that hinders unattended execution. To overcome these limitations, the integrated multilateration method has been introduced, which addresses these challenges and reduces measurement uncertainty. This method offers the potential for fully autonomous volumetric error mapping of large-size machines and enables the development of new functionalities such as traceable coordinate measurement with large machine tools. This research presents the roadmap followed by the authors to automate the volumetric error mapping process for large machine tools. It outlines the current status of the technology, starting from the conceptual development and culminating in the experimental results obtained from real industrial machine tools.

Keywords:
Machine Tool, Volumetric error, Automatization, Accuracy

1 INTRODUCTION

Strategic projects in various sectors such as energy, aeronautics, and scientific research organizations like ITER and CERN have an increasing demand for larger machine tools (MT) capable of achieving higher precision in the manufacturing of bigger and more complex high-value components [1].

McKeown et al. introduced the term "volumetric accuracy" to describe a machine's capability to produce precise 3D shapes [2]. Since then, precise and traceable metrology procedures have been developed to ensure and enhance volumetric accuracy. These procedures involve characterizing the machine tool or employing compensation techniques to improve its performance.

Enhancing the volumetric accuracy of machine tools necessitates the use of suitable measurement methods for characterizing large machine tools. Presently, there exist various technologies and measurement methods to assess the geometrical errors in a serial kinematic configuration machine. As noted by Schwenke et al. [3], these methods can be categorized as "direct" and "indirect."

Direct methods enable the measurement of mechanical errors for a single machine axis without involving other axes. On the other hand, indirect measurements necessitate the movement of multiple axes of the machine being characterized.

Indirect measurement methods offer the advantage of providing fast and reliable assessment of volumetric error performance for medium and large-scale machine tools. In contrast, direct measurement methods are often time-consuming and come with significant limitations.

Currently, multilateration-based approaches are extensively utilized as the predominant techniques for characterizing large-size machine tools [3]. This approach relies on interferometric displacement measurements between fixed reference points on the machine base and offset points located near the TCP (Tool Center Point) on the machine spindle. For comprehensive volumetric verification, a minimum of four measuring systems is required. However, in practical scenarios, usually only one measuring device is available, leading to sequential multilateration measurements.

In the sequential scheme, machine movements are repeated multiple times, and measurements are taken from various positions. While this approach is commonly employed, it presents certain limitations, including significant time consumption, the requirement for MT repeatability, and potential MT drift resulting from thermal variations during the measuring process.

Simultaneous multilateration, on the other hand, overcomes some of these limitations by utilizing four measuring devices simultaneously. This approach offers advantages such as reduced total time consumption, decreased dependency on MT repeatability, and mitigation of MT drift caused by thermal variations.

This paper showcases the work conducted by the authors in developing an integrated multilateration error mapping approach that involves directly attaching a tracking interferometer to the spindle of a manufacturing system. The initial concept was validated by comparing it to the traditional multilateration approach on a large machine tool. Building upon this validation, further research was undertaken, resulting in the development of the Machine Tool Integrated Inverse Multilateration (MIIM) method, which represents an automated and continuous solution. This approach, as described by Mutilba et al. [4], has been enhanced and refined over subsequent investigations to achieve a fully automated mode of operation, allowing uninterrupted measurements to be performed over several days.

2 CLASIC MULTILATERATION

2.1 Multilateration

The volumetric 3D positioning error of a machine is evaluated by comparing the measured spatial data with the nominal values. The widely adopted approach for determining the 3D positions of a predefined grid of points representing the measurement volume is multilateration [5]. In this method, the pure distance between each of the N selected points and the M fiducial points (typically four) is measured, resulting in Equation (1).

$$\left(D_{ij} - L_{offset}\right)^2 = \left(P_{ix} - T_{jx}\right)^2 + \left(P_{iy} - T_{jy}\right)^2 + \left(P_{iz} - T_{jz}\right)^2 \qquad (1)$$

wherein:

- D_{ij} is a pure distance measurement taken from point i of the point grid to fiducial point j with the tracking interferometer. Therefore, there are N x M distance measurements, since N is the number of points in the point grid, 1 < i < N, and M is the number of fiducial points, 1 < j < M.
- L_{offset} is an initial offset value for any interferometry-based measurement since interferometers measure relative values. If an absolute distance measurement system is used, $L_{offset} = 0$.
- T_j is the position of fiducial point j, 1 < j < M.
- P_i is the position of point i of the point grid, 1 < i < N.

The resulting system of nonlinear equations is overdetermined, allowing for the determination of the 3D position of all the points as well as the length residuals that do not conform to the system. These length residuals provide valuable information about the measurement accuracy, which can be further analysed through a straightforward numerical analysis using Equation (2).

$$L_{res} = D_{ij} - L_{calculated} \qquad (2)$$

- L_{res}= Residual of pure length measurement.
- D_{ij}= Actual length measurement taken by the tracking interferometer.
- $L_{calculated}$= Length measurement for every ij distance, calculated as the difference between P_i and T_j after solving Equation (1).

2.2 Equipment

Currently, three types of tracking interferometers are commonly utilized in large-scale metrology for multilateration purposes. Each of these interferometers offers different levels of uncertainty (U) in spatial displacement measurements.

Laser tracer: U (k = 2) = 0.2 µm + 0.3 µm/m

Absolute distance meter (ADM)-based laser tracker: U (k = 2) = 10 µm + 0.4 µm/m

Absolute interferometer (AIFM)-based laser tracker: U (k = 2) = ± 0.5 µm/m

This research was conducted using a Leica AT960 AIFM based middle range (0 to 20 m) laser tracker.

3 SEQUENTIAL APPROACH

Multilateration-based measurement for machine tool error mapping requires a minimum of four fixed points for displacement measurement. These fixed points can be absolute or relative, and measurements are taken between these fixed points and a movable measuring point. In the conventional approach, tracking interferometers are typically positioned on the machine tool table at the locations of the fixed points, while a measuring reflector is attached to the moving spindle to represent the movable points. This configuration, known as classic multilateration, presents a challenge for achieving an automated MT calibration solution as it involves manual intervention to attach tracking interferometers to each measurement station.

In practice, due to the limited availability of tracking interferometers, multilateration measurements are often performed in a sequential scheme. This means that the MT movements are repeated multiple times to the same positions, and measurements are taken from different tracking interferometer locations. However, this sequential approach leads to increased time consumption during measurements and introduces distorsions on the machine between sequential measurements due to thermal changes. This presents a second barrier to an automated solution as it requires MT repeatability to ensure accurate multilateration results. Figure 1 illustrates the classic sequential multilateration approach carried out with a laser tracer NG from ETALON AG on a ZAYER Kairos large MT, showcasing two of the four different laser tracer positions.

Fig. 1 Sequential Multilateration on a ZAYER KAIROS MT.

4 SIMULTANEOUS APPROACH

The simultaneous multilateration scheme can be employed when four tracking interferometers are available simultaneously. Although results are not obtained in real-time and require mathematical post-processing after data acquisition, this approach overcomes several limitations associated with sequential multilateration. It eliminates the need for extensive time consumption, mitigates the requirement for MT repeatability, and minimizes MT distortion resulting from thermal variations during the measuring process.

In the simultaneous approach, each point in the measurement grid is moved to in a unique movement, resulting in a significant reduction in the total acquisition time of up to 75%. Additionally, measurement uncertainties are improved as the impact of thermal effects, especially on the machine tool side, is reduced. Thermal distortion is typically proportional to time consumption, particularly in non-controlled shop floor environments [6].

However, the cost associated with the simultaneous multilateration approach is high. It necessitates the simultaneous operation of four tracking measurement systems and the attachment of two reflectors to the MT spindle.

This cost factor serves as the main barrier preventing widespread adoption of this approach for mapping the volumetric geometric error of machine tools. Figure 2 illustrates a simultaneous multilateration approach implemented on a ZAYER KAIROS large machine tool, where four tracking measurement systems are operating simultaneously. On this case three laser trackers (M1, M2, M3) and one laser tracer (M4) were employed to perform this simultaneous multilateration measurement.

Fig. 2 Simultaneous Multilateration on a ZAYER KAIROS MT.

5 MACHINE INTEGRATED INVERSE MULTILATERATION

5.1 Definition

The Machine Integrated Inverse Multilateration (MIIM) approach, developed by Mutilba et al. [2], is an integrated multilateration verification procedure that involves directly attaching an absolute interferometer to the machine tool spindle, as illustrated in Figure 3.

In this approach, the MT forms a volumetric point grid, and the measurement device is sequentially moved by the MT to various positions. From each of these positions, the distance to every fiducial point fixed on the MT is measured using the attached absolute interferometer [7].

The evaluation of positioning errors in this research is based solely on distance information, without utilizing the tracker encoders' information. The assessment of the machine tool's (MT) linear and angular errors is conducted using different kinematic models specific to the MT being studied.

5.2 MIIM prototype

An initial prototype of the integrated approach concept was carried out on a MEMPHIS machine tool at the premises of ZAYER MT manufacturer. The point grid that was measured consisted of 64 points within the working range of the machine tool, which was mapped as follows: X = 3.000 mm, Y = 2.300 mm, and Z = 900 mm. Two different approaches were employed to measure the same machine:

Classic approach: The MT volumetric error mapping was performed using a laser tracer NG from ETALON AG. Four measurement positions were used, and the total acquisition time was 3 hours.

Integrated multilateration approach: The integrated multilateration approach was executed for the first time using a LEICA AT960 laser tracker fixed to the MT spindle in an upside-down configuration.

Four cateye reflectors were employed as fiducial points, with three of them fixed to the floor and the fourth one fixed outside the floor plane to enhance measurement accuracy in the vertical direction. The total time consumption for the integrated approach was 25 minutes. Figure 3 shows the integrated approach validation exercise.

The comparison between the two approaches demonstrated the significant reduction in time consumption achieved with the integrated multilateration approach, while still providing accurate measurement results.

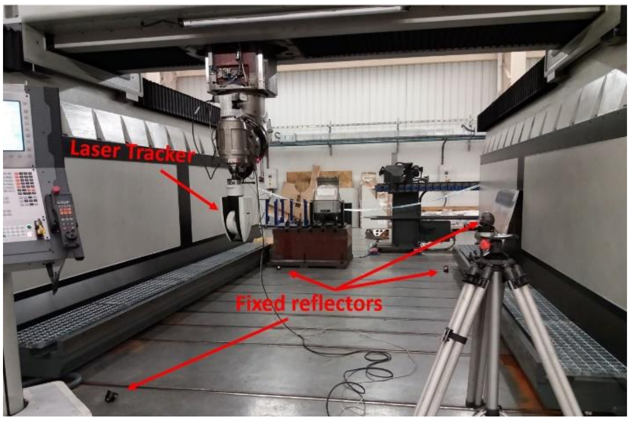

Fig. 3 Integrated Multilateration on a Zayer Memphis MT.

Three specific results were compared between the classic approach and the integrated approach:

a) The standard deviation of pure length measurements was 1.1 µm for the classic approach and 2.47 µm for the integrated approach. This difference can be attributed to the fact that three points were not correctly measured by the integrated approach when conducted manually, leading to poorer results in the fitting process.

b) The uncertainty results after multilateration of the fiducial points and the point grid were found to be better for the integrated approach compared to the classic approach. This improvement can be attributed to the reduced measurement time of 25 minutes, which is five times shorter than the classic approach. The reduced measurement time helps minimize the influence of thermal drift, resulting in more accurate uncertainty results.

c) A comparison between the point clouds generated by both approaches was conducted to understand the differences. The standard deviation between the point clouds was found to be 0.04 mm, indicating a relatively small difference between the two approaches in terms of spatial accuracy.

Overall, these results demonstrate that the integrated approach offers advantages in terms of reduced measurement time and improved uncertainty results. The comparison of point clouds also indicates a good level of consistency between the two approaches.

5.3 Uncertainty budget – method improvement

In order to develop a time- and cost-effective measurement strategy for the MIIM approach, a comprehensive study of the uncertainty sources is crucial.

These uncertainty sources include:

a) The number of fiducial points considered in the measurement process,

b) The thermal drift of the fiducial points,

c) The instrument error model,

d) The size of the machine tool (MT), and

e) The resolution of the equation system.

The simulation is conducted on the ZAYER ARION G portal-type machine tool, which is a 5-axis multitasking machine located at the Tekniker technology centre shop floor. Figure 4 provides a visual representation of the machine tool being used in the simulation.

It serves as a suitable platform for investigating the performance and effectiveness of the proposed MIIM approach. With its advanced capabilities and precise control over multiple axes, it offers a realistic environment for conducting simulations and evaluating the impact of various factors on measurement accuracy.

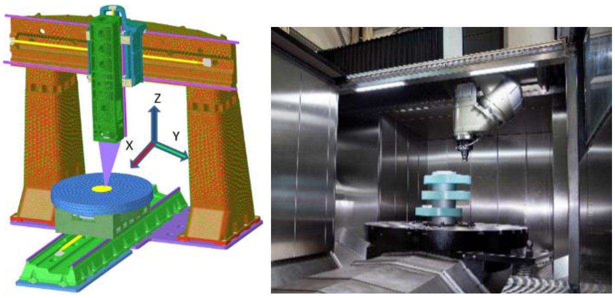

Fig. 4 a) the ZAYER ARION G MT FEM Model and b) the MT at Tekniker facilities.

To simulate the impact of the number of fiducial points on the MIIM approach, an Absolute interferometer (AIFM)-based laser tracker is employed, and a total of four to eight fiducial points are considered.

Figure 5 displays the maximum expanded uncertainty U (k = 2) value on the point cloud for different numbers of fiducial points.

The simulation results indicate that the difference in uncertainty between the options is within a few microns. This suggests that introducing more fiducial points does not significantly improve the obtained uncertainty. Therefore, the recommendation is to maintain the number of fiducial points at four, which minimizes the time consumption of the measurement process.

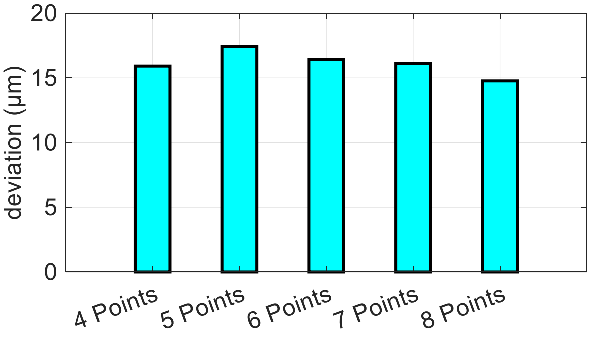

Fig. 5 Influence of the number of fiducial points on the MIIM expanded measurement uncertainty.

The stability of the fiducial points in the MIIM measurement process is influenced by ambient temperature variations. To investigate the impact of thermal gradients, the Finite Element Method (FEM) is employed to simulate the distortion of the fiducial points located on the turning table of the ARION G machine tool.

The turning table, with a diameter of 2 meters, is independent of the portal structure and constructed from cast iron. The linear thermal expansion coefficient (α) is assumed to be 10 µm/m°C.

In the simulation, four different scenarios were considered to represent the distortions caused by varying ambient temperatures:

a) No temperature variation (0°C) resulting in 0 µm deformation.

b) Temperature variation of 1°C leading to a deformation of 20 µm.

c) Temperature variation of 2°C resulting in a deformation of 40 µm.

d) Temperature variation of 3°C causing a deformation of 60 µm at the fiducial points on the turning table.

Figure 6 illustrates the measurement uncertainty of the MIIM method for these different temperature variation scenarios. The maximum value of the expanded uncertainty U (k = 2) on the point cloud is reported.

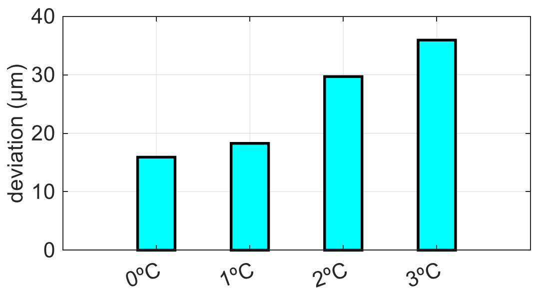

Fig. 6 Influence of fiducial point thermal drift on MIIM expanded measurement uncertainty.

By analysing the simulation results, it becomes possible to understand the impact of thermal gradients on the measurement uncertainty of the MIIM approach. This information is crucial for developing strategies to mitigate the effects of temperature variations and ensure accurate and reliable measurements. Results show that for a temperature variation of 1ºC the MIIM measurement uncertainty introduces a small increment compared to a non-variant temperature measurement process with a variation of 2.3 µm.

By thoroughly understanding and analysing these uncertainty sources, it becomes possible to develop an optimized measurement strategy for the MIIM approach, ensuring accurate results while minimizing time and cost requirements.

6 MIIM VALIDATION

In order to validate the simulation results and assess the feasibility of the MIIM approach in a real-world scenario, a practical integration exercise was conducted on a ZAYER ARION G large machine tool, employing a Leica AT960 laser tracker, available at TEKNIKER premises. The integration process involved the placement of four wide-angle reflectors on the machine tool table, with one reflector positioned out of the plane. The laser tracker was securely attached to the MT spindle, facing upward, using a specially designed stiff fixture to ensure the tracker's position remained fixed relative to the tool center point (TCP) during spindle movements.

To streamline the measurement process and eliminate human intervention, the measurement procedure was automated using SA software. This automation allowed for efficient execution of the measurement process within a timeframe of just 30 minutes. Figure 7 provides a visual representation of the actual integration exercise, showcasing the placement of the four wide-angle reflectors on the machine tool table and the LEICA AT960 tracker fixed to the MT spindle.

By performing the real integration exercise, researchers were able to validate the practical implementation of the MIIM approach and further validate its accuracy and reliability in a real-world industrial setting. The exercise demonstrated the potential for automating the MT error mapping process and achieving precise and efficient volumetric error characterization of large machine tools.

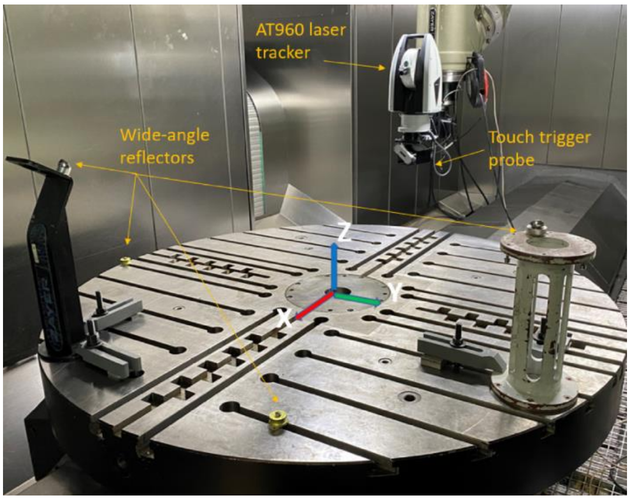

Fig. 7: Real integration exercise within the ARION G machine tool with a LEICA AT960 laser tracker.

The manuscript does not include the depiction of specific results and findings due to confidential considerations. The authors respect the confidentiality agreements with the industrial partners involved in the research, which restrict the public disclosure of detailed results and data.

Further research has recently been initiated to extend this methodology to real industrial environments and larger machines. An exemplary demonstration of these advancements can be seen in Figure 8, which illustrates one of the latest measurement exercises conducted at the ZAYER assembly shop floor.

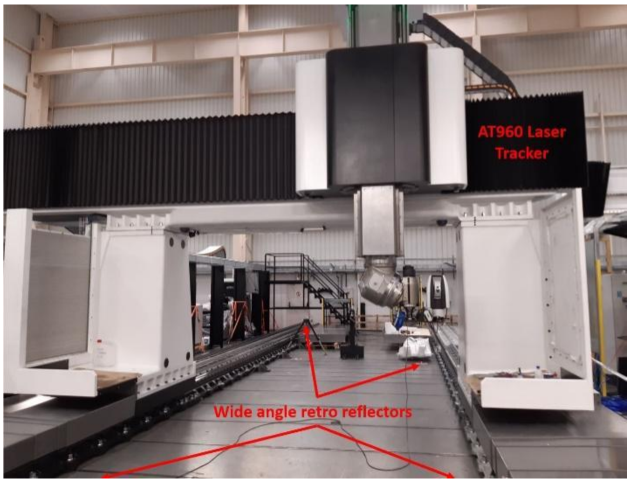

Fig. 8: Real integration exercise within the ZAYER THERA machine tool with a LEICA AT960 laser tracker.

The total number of points in the point cloud can be adjusted according to the specific requirements of the test. For instance, when rapid temperature changes are involved, fewer points can be used to reduce the overall measurement time. Conversely, for slower temperature changes and improved spatial resolution, a higher number of points is necessary in each measurement sequence.

In this particular case, the measured volume and resolution for each axis were as follows, with a focus on achieving high resolution for the machine ram displacement along the Z vertical axis:

a) X: -14.700 to -8.700 (6.000mm) with a step size of 1.000 mm.

b) Y: -3.400 to -400 (3.000mm) with a step size of 500mm.

c) Z: -1.460 to -60 (1.400mm) with a step size of 200mm.

The number of repetitions can also be configured, ranging from a single measurement to an "infinite" number of measurements. To ensure the robustness of the solution, continuous measurements have already been conducted in automated and unattended mode for more than five days.

Figure 9 displays the point cloud configuration distributed across the XY, XZ, and YZ planes, positioned at the mid-range of each axis. This configuration facilitates subsequent inverse kinematic (IK) exercises aimed at solving the MT kinematic parameters, which can potentially enable volumetric correction.

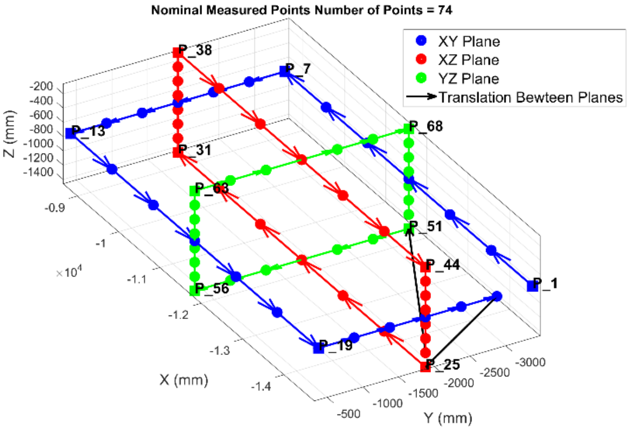

*Fig. 9: MIIM test point cloud configuration for **7**4 measurement points.*

7 CONCLUSIONS

This article introduces the application of the developed Machine Tool Integrated Inverse Multilateration (MIIM) method for the automated, rapid, accurate, and volumetric characterization of large machine tools, while minimizing the influence of thermal errors. The research demonstrates the feasibility of achieving automated volumetric verification and calibration with uncertainties within the micrometer range. In comparison to typical multilateration approaches, the MIIM method offers several significant advantages:

- Reduced Data Acquisition Time: The total time consumption during data acquisition is reduced by 75% due to the need for only a single movement of the point grid.

- Improved Uncertainty in Multilateration Results: The MIIM approach reduces thermal drift during data acquisition, particularly on the manufacturing system side. This reduction in thermal drift leads to improved uncertainties in the multilateration results. In a non-controlled shop floor environment, thermal drift is proportional to time consumption.

- Automated Data Acquisition: The MIIM method eliminates the need for human intervention during the data acquisition process. The laser tracker is automatically moved to each measurement position, enhancing efficiency and reducing the potential for human errors.

By leveraging the MIIM method, the article highlights the potential to achieve automated, fast, and accurate volumetric characterizations of large machine tools while effectively mitigating the impact of thermal errors. These advancements have significant implications for enhancing the calibration and verification processes in the manufacturing industry.

It also opens a great opportunity to characterize the machine volumetric errors in large periods of time.

8 SUMMARY

This manuscript provides a comprehensive roadmap outlining the evolutionary journey undertaken by the authors to develop an automatic volumetric error mapping process for large machine tools. It encompasses the entire spectrum of the technology, starting from its conceptual development and concluding with the experimental results obtained from real-world industrial machine tools.

9 ACKNOWLEDGMENTS

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