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A comparison of the performance of tool pre-setting optical systems: On- and off-machine tool assessment

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Abstract

Tool geometry can be determined off-machine using tool pre-setters by mounting the cutting tool on the tool holder; however, such arrangement introduces the unquantified clamping errors associated with the interface between the tool holder and the machine tool spindle and affecting the precision of machining processes. Thus, on-machine integrated tool pre-setting systems are important to accomplish reliable and accurate tool measurements and attaining the desired accuracies in the machining operations. These days, machine tools are normally equipped with tool pre-setting optical systems such as laser beam interruption systems or camera-based systems; however, the traceability of such optical sensors is not guaranteed due to the lack of a specific international standard. In this work, we have evaluated the performance of camera-based tool pre-setting optical systems for on- and off-machine scenarios. The measurement procedure resides on the guidelines specified in ISO 15530 part-3 which provides a method of uncertainty evaluation using calibrated artefacts or standards. For this purpose, a reference artefact with a square cross-section is designed from a cylindrical gauge pin (Ø6 mm ± 1 µm) and machined into a square end by wire EDM. The reference artefact is mounted on a tool holder and calibrated using a coordinate measuring machine by repeating measurements twenty times and the task-specific uncertainty is determined. The calibrated artefact is later employed to evaluate the performance of the tool pre-setting optical systems for on- and off-machine instances. Experiments have shown the implication of the developed approach for the characterisation of tool pre-setting optical systems for tool geometry assessment.

Tool pre-setting optical system, coordinate metrology, reference artefact, uncertainty, machine tool, runout.

1. Introduction

Accurate tool geometry estimation is of paramount importance in machining operations as the surface generation and the surface quality of the manufactured parts is highly dependent on the accurate tool data. Tool geometry can be determined on- and off-machine using tool pre-setters and with the tool mounted on the tool holder. However, in case of off-machine tool, the interface between the tool holder and the machine tool spindle introduces additional errors contributing to unidentified machining errors. Thus, on-machine integrated, and traceable tool pre-setting optical systems are essential to address the limitations and achieving reliable accurate tool data to accomplish the precise machining procedures.

These days, the modern computer numerical control (CNC) machine tools are equipped with non-contact tool pre-setting optical systems such as the laser beam interruption systems, laser scan micrometres and the camera-based systems for on-machine tool pre-setting. However, traceability of such instruments is not guaranteed due to lack of the international standards [1]. In this work, the performance of the camera-based tool pre-setting optical systems for on- and off-machine tool scenarios is evaluated (using ISO 15530 part 3) residing on a comparator approach from the reference measurements (coordinate measurement machine, CMM). The uncertainty contributors from the measurement procedure were computed and the task-specific uncertainty evaluation is performed.

2. Materials and methods

The methodology of this work resides on validating the performance of on- and off-machine tool pre-setting optical systems based on a comparator approach by utilising the ISO 15530 part-3 [2]. For this purpose, an artefact is designed using a cylindrical gauge pin of diameter (Ø6 mm ± 1 µm) and the nominal length of 70 mm and machined into a square cross section. The artefact is calibrated on a coordinate measuring machine using a developed approach called *the virtual plane approach* and later employed to evaluate the metrological characteristics of the on- and off-machine tool pre-setting systems. The details of the measurement strategy and the instruments utilised are provided in the subsequent sections.

2.1. Tool pre-setting optical systems

In this work, two camera-based tool pre-setting optical systems are used which are mounted on- and off- machine tool. Figure 1 shows a photograph of the camera-based tool pre-setting optical system mounted on KERN Micro Vario (KERN Microtechnik GmbH, Germany) whilst the off-machine tool optical system is shown in Figure 2. and placed in the shopfloor environment for tool pre-setting measurements. The on-machine tool optical system has a protective enclosure and designed to function inside the machine tool's harsh environment such as cutting fluid, metal chips and the coolant droplets.

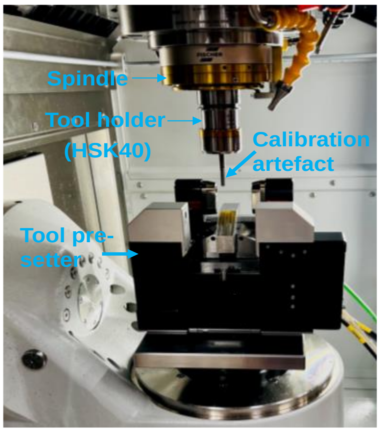

Figure 1. Experimental setup of the camera-based tool pre-setting optical system mounted on the rotating table of the machine tool (KERN Micro Vario).

Off-machine tool pre-setter is a camera-based tool pre-setting system that measures and transfers the tool data to the CNC machines. The system has a universal spindle and mechanical clamping system which is compatible with all kinds of tool holders through a number of connecting plates. Additionally, the system does not need recalibration due to temperature variations, yielding precise and repeatable measurements without software compensation needed for correcting the mechanical misalignment.

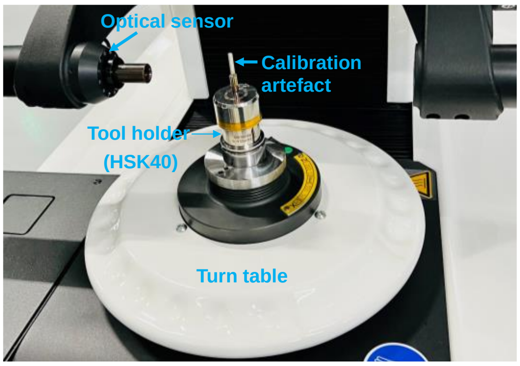

Figure 2. Experimental arrangement for the camera-based tool pre-setting optical sensor for off-machine measurement.

2.2. Coordinate measuring machine

Figure 3 shows a photograph of the experimental setup in which the artefact is mounted on a tool holder (HSK40) and the assembled arrangement (artefact on the tool holder HSK40) is regarded as an actual artefact and placed over a fixture to perform the CMM measurements on ZEISS Varity (MPE: (0.7 ± L/450 µm, L in mm)). The CMM measurements are used as a reference to characterise the performance of the on- and off-machine tool optical systems. A T-shaped probe with one vertical stylus and two horizontal styli (all with Ø3 mm spheres) was used, and the measurements were repeated twenty times at an ambient temperature of (20 ± 1) °C, as stated in ISO 15530 part-3 [2, 3].

2.3. Optical 3D surface profilometer

An optical 3D surface profilometer (Alicona CMM-005-Bruker, Infinite Focus G4) with 50x magnification and a working distance of 10.1 mm was used to examine and quantify the edges of the square cross section of the calibration artefact (artefact mounted on a tool holder HSK40) and shown in Figure 4. The working principle of the optical 3D profilometer resides on the focus variation method [4] and the optical instrument can provide accurate and repeatable optical 3D surface measurements. The traceability of Alicona resides on the calibration and the verification certificate, and the instrument is calibrated using IF-Calibration Tool [5].

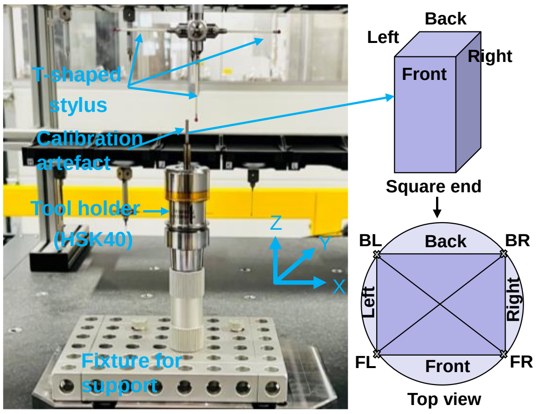

Figure 3. Experimental assembly for CMM measurement with the actual artefact (artefact + tool holder HSK40) mounted on a fixture.

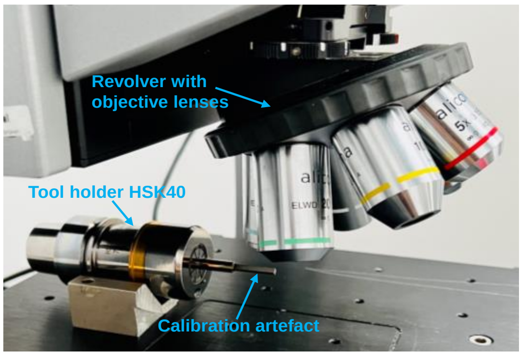

Figure 4. Experimental setup of edge radius measurement of the calibration artefact mounted on the tool holder HSK40 using Alicona Infinite Focus G4.

2.4. Calibration artefact design

An artefact was manufactured from a cylindrical gauge pin with a diameter of 6 mm ± 1 µm and a length of 70 mm and shaped into a square cross section by wire electrical discharge machining (WEDM) on AgieCharmilles CUT 2000 Oiltech.

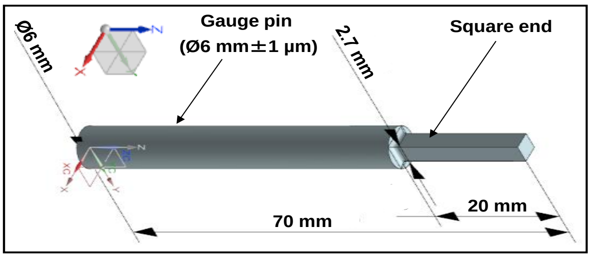

Figure 5. CAD model of the calibration artefact [6].

The artefact has a square profile with four edges (similar to a flat end mill with four cutting edges but without the helix angle. Figure 5 depicts a photograph of the artefact with the side length of the square cross section as 2.7 mm, yielding a nominal diagonal length of 3.818 mm which is compatible with the field-of-view of the camera-based tool pre-setting system (Tool diameter ≤ 4 mm) specifically the optical sensor mounted on the machine tool.

2.5. Task-specific uncertainty evaluation for tool pre-setting optical systems

The validation tests for evaluating the performance of the tool pre-setting optical systems reside on ISO 15530 part-3 which simplifies the uncertainty estimation process chain based on the similarity criteria (dimensions, form, shape) between the actual artefact and the calibrated one (reference artefact), and the measurements are performed similarly to the actual measurements. In general, based on the CMM measurements, four uncertainty contributors to the overall measurement uncertainty are considered and the expanded uncertainty according to ISO 15530 part-3 [2] is given by the following expression,

$$U_M = k\sqrt{u_{cal}^2 + u_b^2 + u_p^2 + u_w^2} \qquad (1)$$

where k is the coverage factor ($k = 2$ for 95% confidence of interval), u_{cal} denotes the standard uncertainty of the calibrated artefact, u_b represents the standard uncertainty of the systematic error in the measurement process; generally, ($u_b = b = \bar{x} - x_{cal}$) when measurements are not corrected for systematic error, u_p is the standard uncertainty of the repeated measurement ($u_p = (s/\sqrt{N})$, s is the standard deviation and N is the number of measurements conducted [8, 9]), and u_w is the standard uncertainty associated with the material and manufacturing changes.

In equation (1), the standard uncertainty of the calibration artefact u_{cal}, can be computed as,

$$u_{cal} = \sqrt{u_{CMM_{cal}}^2 + u_{Alicona_{cal}}^2} \qquad (2)$$

whereby u_{CMMcal} is the calibration uncertainty in the CMM measurements and given by,

$$u_{CMMcal} = \sqrt{u_{CMM_{rp}}^2 + u_{CMM_{pr}}^2 + u_{CMM_{sc}}^2 + u_{CMM_{sys}}^2} \qquad (3)$$

$$= \sqrt{(0.06)^2 + (0.4)^2 + (0.5)^2 + (0.36)^2} = 0.74\ \mu m \qquad (4)$$

where $u_{CMM_{rp}}$ depicts as the uncertainty in the repeated CMM measurements, $u_{CMM_{pr}}$ is the uncertainty in the probe qualification, $u_{CMM_{sc}}$ is the scanning probe error, $u_{CMM_{sys}}$ is related to the systematic error (0, 0.3, -0.2) µm in the x, y and z directions (distance: (80, 80, 121) mm), respectively.

Likewise, for focus variation profilometer, the calibration uncertainty is given by,

$$u_{Alicona_{cal}} = \sqrt{u_{Alicona_{lat}}^2 + u_{Alicona_{vert}}^2} \qquad (5)$$

$$= \sqrt{(0.25)^2 + (0.5)^2} = 0.6\ \mu m \qquad (6)$$

where $u_{Alicona_{lat}}$ ($U_{Alicona_{lat}}/2$), $u_{Alic_{vert}}$($U_{Alic_{vert}}/2$) are the deviations (in µm) for the lateral (50x lens), and vertical (10x lens) calibration with reference to the IF-CalibrationTool [5].

Therefore, the calibration uncertainty u_{cal} (given in equation (2)) is computed as 0.95 µm using equations (3) and (5).

3. Experimental tests and the outcome

Figure 1 and Figure 2 depict the photographs of the camera-based tool pre-setting optical systems for the on- and off-machine tool configurations, respectively; whilst Figure 3 shows the experimental arrangement for CMM measurements whereby the calibration artefact is mounted on a tool holder (HSK40). A comparator-based approach has been developed based on ISO 15530 part-3 which provides a method of uncertainty evaluation using the calibration artefacts and measurement standards [2]; and applied to validate the performance of the camera-based tool pre-setting optical systems. The methodology resides on the task-specific uncertainty evaluation through a series of repeated CMM measurements (20 repeats) and later utilising them to evaluate the performance of the camera-based tool pre-setting systems for the on- and off-machine scenarios.

In order to accomplish the similarity criteria as recommended by ISO 15530 part-3, the artefact was mounted on a tool holder (HSK40) and the whole assembly (artefact on the tool holder) is regarded as an artefact, on which the repeated CMM measurements were performed; initially to calibrate the artefact and later to use it as a reference for validating the performance of the camera-based tool pre-setting optical systems both for the on- and off-machine tool situations. The calibration artefact (artefact + tool holder) was later placed in the spindle of the machine tool to conduct the repeated measurements (20 repeats) on the camera-based tool pre-setting system mounted on the machine tool, as well as on an off-machine tool pre-setter.

The CMM measurement process includes the probe qualification (according to manufacturer's specification), manual base alignment followed by the automated base alignment and estimating various feature characteristics (within repeatability of 0.21 µm, 95% confidence of interval). The reference coordinate system was specified with respect to the top plane (XY plane) of the square cross section of the calibration artefact with Z-direction pointing upwards. To compute the parameter of interest (artefact's effective radius), a virtual plane approach is used [6]. For this purpose, a theoretical plane is defined at a Z-height of 0.2608 mm (away from the top XY plane of the square end, Figure 3), and the intersection point of the theoretical plane located at 0.2608 mm and the two outer tangential orthogonal planes (BL, FR, BR, FL shown in Figure 3) is computed.

The radius of the square end (Z-height 0.2608 mm where the on-machine tool optical sensor computes the tool geometry) is measured as the largest radial distance from the centre of the tool holder to the edge of the square end of the artefact whilst the runout is the difference between the largest and the smallest measured radii. The measured results are given in Table 1.

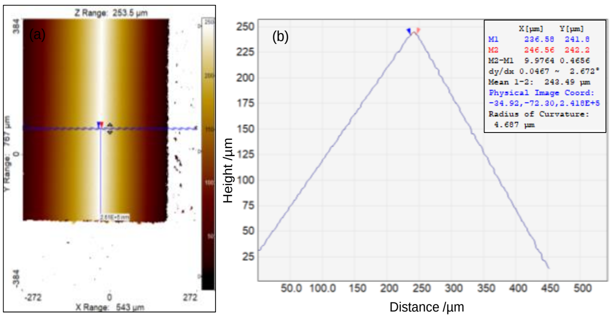

Figure 6. (a) Image of the front left (FL) edge of the square end by 3D surface profilometer, and (b) processing in SPIP by averaging a region-of-interest of 6 µm.

The edge radius (corner radius of the four edges of the square end) impact is incorporated in the measurement process (20 repeats, Table 1) and quantified using an optical 3D surface profilometer [6, 7] as shown in Figure 6.

Table 2 depicts a comparison of the measured results of the artefact's effective radius and the runout for on- and off-machine tool pre-setters for 20 repeated measurements. The difference of the on-machine tool measured outcome from the reference data (CMM) is 2.5 µm and 0.4 µm for the artefact's effective radius and the runout, respectively, whilst this difference is 0.4 µm, 1.5 µm, respectively, for the off-machine tool pre-setter. By incorporating the systematic bias with the other uncertainty contributors (equation (1)), the expanded uncertainties are 5.3 µm, and 2.1 µm in the measured artefact's effective radius and the runout, respectively, for on-machine

Table 1. Measured geometry of the calibration artefact residing on the virtual plane approach.

Edge name of the calibration artefact	Radial distance - Tool holder centre to the edge of the square end (Mean of 20 repeats) /mm	Edge radius, r_c (Mean of 20 repeats) /µm	Edge radius contribution - $r_c(\sqrt{2}-1)$ /µm	Effective radius of the calibration artefact with edge radius included /mm	Runout /µm
Back Right (BR)	(1.9017 mm ± 0.14 µm)	(4.69 ± 0.03)	(1.94 ± 0.03)	(1.8998 mm ± 0.14 µm)	(9.5 ± 0.26)
Front Left (FL)	(1.9112 mm ± 0.13 µm)	(4.68 ± 0.03)	(1.94 ± 0.03)	(1.9093 mm ± 0.13 µm)	
Back Left (BL)	(1.9085 mm ± 0.10 µm)	(5.22 ± 0.02)	(2.16 ± 0.02)	(1.9063 mm ± 0.10 µm)	
Front Right (FR)	(1.9051 mm ± 0.11 µm)	(6.20 ± 0.03)	(2.57 ± 0.03)	(1.9025 mm ± 0.11 µm)	

Table 2. A comparison of the measured outcome of the on- and off machine tool pre-setting systems.

	On-machine tool pre-setter		**Off-machine tool pre-setter**	
Type	**Artefact radius /mm**	**Runout /µm**	**Artefact radius /mm**	**Runout /µm**
Mean (20 repeats)	1.9118 mm	9.9 µm	1.910 mm	8 µm
u_{cal}	0.95 µm	0.95 µm	0.95 µm	0.95 µm
u_b	2.5 µm (1.9118 -1.9093)	0.4 µm (9.9 – 9.5)	0.7 µm (1.910 – 1.9093)	-1.5 µm (8 – 9.5)
u_p	0.03 µm	0.03 µm	0.14	0.18
u_w	insignificant	Insignificant	Insignificant	Insignificant
$U_M(k=2)$	5.3 µm	2.1 µm	2.4 µm	3.6 µm

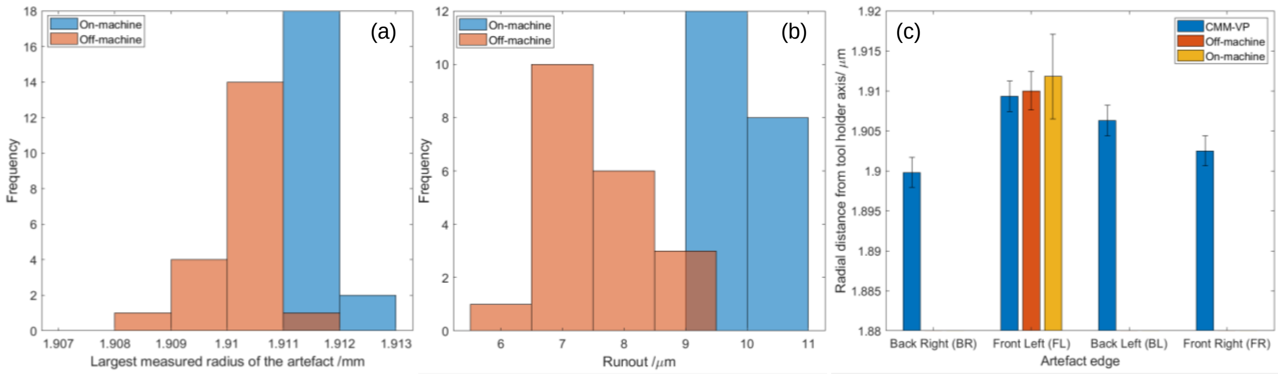

Figure 7. Statistical distribution for on- and off-machine tool pre-setters. (a) Artefact's effective radius, (b) runout, and (c) a comparison of the artefact's measured effective radius.

whilst 2.4 µm and 3.6 µm (Table 2) for the off-machine tool pre-setter. The statistics of the measured outcome of the on- and off-machine tool is shown in Figure 7(a-b) which indicates the on-machine tool pre-setter has a relatively narrow spread in contrast to the off-machine tool, corresponding to better repeatability of the optical pre-setter. Figure 7(c) depicts a comparison of the measured radial distance of the square end of the artefact along with measured uncertainties for CMM (the virtual plane approach), on- and off-machine tool pre-setters.

4. Conclusions and future work

In this work, the validation of two camera-based tool pre-setting optical systems have been accomplished by utilising the ISO 15530 part-3, and for on- and off-machine tool scenarios. To fulfil the similarity criteria as stated in ISO 15530 part 3, an artefact was designed using a cylindrical gauge pin, mounted on a tool holder and the whole assembly (artefact + tool holder) is regarded as an artefact and calibrated using CMM. The artefact was later placed on the tool pre-setting optical systems (on-and off- machine tool), and the task-specific uncertainty evaluation of the optical systems is evaluated by comparing the measured outcome with the reference CMM measurements. The results have shown an expanded uncertainty (within 95% CI) of 5.3 µm and 2.1 µm in the measured artefact's effective radius and the runout, respectively, for on-machine while 2.4 µm and 3.6 µm (Table 2) for the off-machine tool pre-setting system. Additionally, the larger bias in the on-machine tool pre-setter is due to systematic error, and an investigation is underway to alleviate the bias.

Acknowledgements

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