

IMPACT OF HIGH ANGULAR RESOLUTION ON TOOL GEOMETRY ASSESSMENT IN AN ON-MACHINE TOOL PRESETTING SYSTEM

Amrozia Shaheen^{1,2*}, and Giuliano Bissacco¹

¹Technical University of Denmark, Department of Mechanical Engineering, 2800 Kgs. Lyngby, Denmark

²LEGO System A/S, Aastvej 1, 7190, Billund, Denmark

*Corresponding author e-mail: amrsh@dtu.dk

Abstract

Tool geometry assessment is essential in machining processes to ensure the accuracy of manufactured parts. Tool presetters such as laser beam interruption systems and camera-based systems are optical systems used to determine the tool geometry and are considered a prerequisite for machining operations. Tool geometry can be measured both on- and off-machine; however, on-machine tool presetting is preferred as the interfaces between the tool holder and the machine tool spindle can introduce unquantified clamping errors that affect the precision of machining processes. In this work, we compare the effect of high angular resolution on the performance evaluation of a camera-based tool presetting optical system for on-machine measurement of ball end mills. The validation process follows the guidelines stated in ISO 15530 part 3 and is established using a calibrated artefact which resembles a ball end mill (without the helix angle), whilst the reference measurements are performed using a coordinate measurement machine, and the task-specific uncertainty is determined. Experimental results have shown that the tool geometry measurement process (tool radius, runout) performs better when using the high angular resolution of the camera-based tool presetting system.

Keywords: Camera-based optical system, tool geometry, coordinate metrology, uncertainty budget

1 INTRODUCTION

High resolution in imaging refers to acquiring images with a very high degree of detail, often exceeding what can be perceived by the human eye [Bradac 2021] [Khonina 2024]. In general, high spatial resolution (pixels per inch, PPI) provides enhanced details that would otherwise be undetectable at low resolutions leading to improved depth and precision in visual data, and plays a vital role in scientific, medical and industrial sectors. Furthermore, the high-resolution imaging supports the interdisciplinary research by integrating the visual data across different domains. In fields such as scanning electron microscopy (SEM), transmission electron microscopy (TEM) and confocal laser scanning microscopy (CLSM) enable researchers to examine the microstructure and composition of materials at the nanoscale [Wang 2024] [Ilie 2019].

In this work, we have developed a method for the performance verification of a camera-based tool presetting optical system at normal and high angular resolutions using the guidelines specified in ISO 15530 part 3. The standard defines a protocol for evaluating the measurement uncertainty for coordinate measuring machine using calibrated artefacts or measurement standards [ISO 15530-3:2011]. Thus, an artefact similar to a ballnose cutting tool was manufactured and calibrated using a coordinate measuring machine (CMM). The method for measuring the parameters of interests (effective tool radius, runout) of the artefact was developed and the uncertainty contributors from the calibration procedure were determined. Additionally, the performance of the camera-based tool

presetter was determined by employing the reference artefact on the on-machine optical system and subsequently comparing the measured tool geometry at different angular resolutions against the reference CMM measurements.

2 MATERIALS AND METHODOLOGY

The methodology for validating the tool presetting system for measuring the tool geometry (tool radius, runout) of ball end mills is based on the similarity criteria between the dimension and the form of the actual artefact and the calibrated reference artefact [ISO 15530-3: 2011], followed by developing the artefact's calibration procedure and evaluating the performance at one- and two-degree angular resolutions of the camera-based optical system. The details are provided in the following sections.

2.1. Camera-based tool presetting system

The camera-based system CU2 Tool M67 (Conoptica AS, Norway) is an inexpensive and a high-speed optical system which is used in the industrial sector as a tool presetter for cutting tool measurement in machining operations. The optical system (mounted on a Fanuc Robodrill α -D21LiB5adv, shown in Fig. 1) consists of a camera and an illumination unit and is capable of performing the on-machine automated tool measurement of the rotating milling tool at the desired spindle speed, and compatible with machine tool harsh conditions (contamination by cutting fluid lubrication, metal chips and air-born coolant droplets). The camera-based system specifications include

an optical magnification of x67, field-of-view $4.5 \text{ mm} \times 2.9 \text{ mm}$, and can measure the cutting tools with tool diameter less than 4mm for simultaneous measurement on both sides of the tool [CU2 Tool Conoptical]. The measurement process comprises illuminating from one side and recording images of the rotating milling tool at different rotation angles. The analysis is executed in CU2 Tool software (integrated with the tool presetter system and provided by the manufacturer) by utilising the reference model and the recorded images information in order to compute the cutting tool geometry.

In this investigation, twenty measurement cycles (stated in ISO 15530-3) are evaluated where each cycle incorporates creating the reference model of the clean tool and subsequently performing the measurement by acquiring images at one-degree (high resolution) and two-degree (normal measurement process of the tool presetter) angular resolutions (Fig. 2). The process comprises of recognising each cutter individually, executing the digital cleaning and computing the tool geometry such tool radius, tool length, radius of curvature, and runout [Shaheen 2024]. We have considered the tool radius and the runout to see the impact of the high angular resolution of camera-based optical system on its tool geometry assessment process.

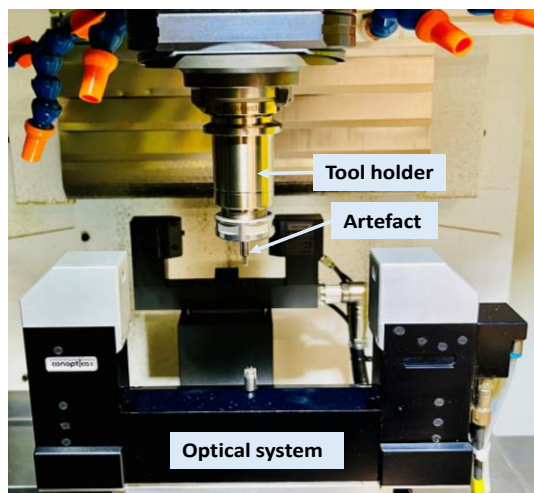


Fig. 1: The camera-based tool presetting optical system with the ballnose shaped reference artefact being mounted in the spindle of the machine tool.

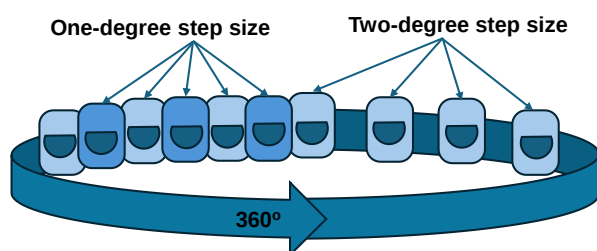


Fig. 2: Schematic of normal and high angular resolutions of the optical system for a full rotation of 360° .

2.2. Reference artefact and measurement details

Reference artefact (ballnose shaped)

Fig. 3 displays the CAD model of the artefact. The reference artefact resembles a ball end mill (without the helix) and consists of a cylindrical gauge pin with a diameter of $\phi 6 \text{ mm} \pm 1 \mu\text{m}$ while the length is 70 mm. The artefact has a square end transitioning into a curved face featuring four cutting edges. The nominal side length of the squared segment is 2.7 mm whilst the nominal diagonal length (also the tool

diameter) is 3.818 mm. The nominal radius of curvature (2^{nd} radius) of the curved segment is 1.909 mm. A simple geometry is selected for the reference artefact to ensure compatibility with the camera-based tool presetting optical system which is capable of measuring milling tools with sharp cutting edges.

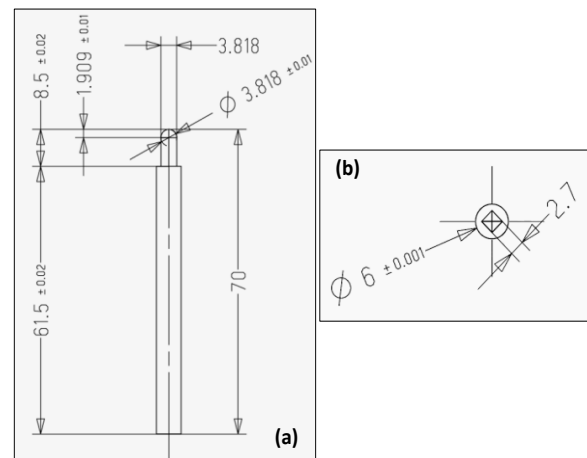


Fig. 3: CAD model of the ballnose shaped reference artefact with nominal dimensions in mm. (a) Front view, and (b) top view.

Reference CMM measurements

A coordinate measuring machine (CMM-001-Zeiss-PRISMO, MPE: $(0.9 + L/350) \mu\text{m}$, L in mm) [ISO 10360-1:2000] [Savio 2002] was used to accomplish the reference measurements for characterising the tool presetting optical system. The experimental arrangement is shown in Fig. 4, and the reference artefact is mounted on a V-shaped magnetic holder being clamped on a vise. Two probes were used; probe-1 comprises of two horizontal styli with $\phi 3 \text{ mm}$ and $\phi 8 \text{ mm}$ spheres (depicted in Fig. 4 (a)) while probe-2 has one horizontal stylus of $\phi 1 \text{ mm}$ sphere and one vertical stylus with $\phi 8 \text{ mm}$ sphere (shown in Fig. 4 (c)).

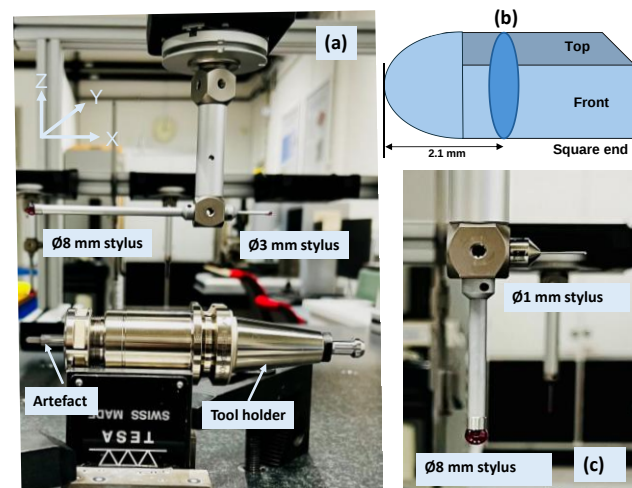


Fig. 4: Experimental assembly for CMM measurements. (a) Probe-1 ($\phi 3 \text{ mm}$, $\phi 8 \text{ mm}$ spheres), (b) a schematic of contour scan approach, and (c) probe-2 with $\phi 1 \text{ mm}$ and $\phi 8 \text{ mm}$ spheres.

Fig. 4 (b) represents a schematic of the contour scan approach where the tool radius is measured at a height 2.1 mm away from the tool tip. The probing was done in scanning mode, and the measurements were repeated twenty times as specified in ISO 15530 part 3, and the

ambient temperature was $(20 \pm 1) ^\circ\text{C}$.

2.3. Uncertainty evaluation of the camera-based tool presetter

The measurement uncertainty for evaluating the performance of the camera-based tool presetter is computed by considering four main contributors, each linked to the random or systematic error. The expanded uncertainty [ISO 15530-3 2011] can be expressed as follows,

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

where k is the coverage factor ($k = 2$ for 95% confidence of interval), u_{cal} is the standard uncertainty of the reference artefact, u_b is the standard uncertainty of the systematic error related to the measurement process ($u_b = b$ if the measurement is not corrected for systematic error, and $b = \bar{x} - x_{cal}$), u_p is the standard uncertainty associated with the measurement is being performed on the calibrated reference artefact ($u_p = \left(\frac{s}{\sqrt{N}}\right)$, s is the standard deviation and N is the number of measurements conducted [ISO JCGM 100:2008] [ISO/IEC Guide 99], whilst u_w is the standard uncertainty of material and manufacturing changes of the measured object such as thermal expansion coefficient, surface roughness, and the form errors.

The calibration uncertainty ($u_{cal} = u_{CMM-cal}$) in the CMM measurements can be expressed as,

$$u_{CMM-cal} = \sqrt{U_{rep}^2 + U_{probe}^2 + U_{scanning}^2 + U_{system(x,y,z)}^2} \quad (2)$$

$$= \sqrt{(0.18)^2 + (0.2)^2 + (0.6)^2 + (0.3)^2} = 0.72 \mu\text{m} \quad (3)$$

where, U_{rep} is the uncertainty in the repeated CMM measurements, U_{probe} is the uncertainty related to probe qualification, U_{scan} is the scanning probing error, $U_{system(x,y)}$ is associated with systematic error in the x , y and z directions.

3 EXPERIMENTS AND RESULTS

Fig. 1 shows the photograph of the camera-based tool presetting optical system while the experimental setup for CMM measurements (serves as a reference) is shown in Fig. 4. We have developed a method for the performance evaluation of the camera-based system for measuring the tool geometry (tool radius and runout) using the reference calibration artefact and measurements (CMM) as stated in ISO 15530-3, and a comparison of the measured outcome for the normal and high angular resolution (increasing the angular step size between the image acquisition of a full rotation) of the optical system has been made. The method resides on determining the task-specific uncertainty by repeating the CMM measurements (our reference) twenty times and using this information for evaluating the performance of the on-machine camera-based tool presetter. The reference artefact was later employed in the spindle of the machine tool (FANUC Robodrive α -D21LiB5adv) and a similar procedure for estimating the tool geometry was adapted by repeating the measurements twenty times on the camera-based tool presetting system.

For CMM measurements, the reference coordinate system was specified on the artefact as shown in Fig. 4 (a) and with respect to the plane at the cylindrical gauge pin face adjacent to the squared parts of the artefact. The CMM

measurement process (our reference) includes probe qualification (according to manufacturer's specifications), manual base alignment followed by the automated base alignment and determining different feature characteristics. The repeatability of the measured features of interests (gauge pin diameter and cylindricity, flatness of four faces of the squared part) is within $0.1 \mu\text{m}$ with 95% of confidence interval and stated in Tab. 1.

Tab. 1: CMM measured outcome of features of interests.

Feature of interest	Measured outcome (average of 20 repeats)	Repeatability (95% CI)
Cylinder diameter	6.0015 mm	0.01 μm
Cylindricity	1.0 μm	0.01 μm
Flatness top plane	2.2 μm	0.07 μm
Flatness bottom plane	1.2 μm	0.03 μm
Flatness front plane	1.7 μm	0.03 μm
Flatness rear plane	2.0 μm	0.04 μm
Effective tool radius	1.9169 mm	0.54 μm
Runout	25.28 μm	1.04 μm

In order to determine the parameters of interests (effective tool radius, runout), a contour scan approach was developed (Fig. 4 (b)). In this technique, the CMM probe scans around the square end at a specific height (2.1 mm away from the tool tip) and the diameter of the square circumscribing circle is determined as the Global Minimum feature [ISO 12181-1:2011] which is the evaluation of measurement points as a minimum circumscribed circle/cylinder (Tab. 1 and Tab. 2).

In order to determine the radial distance from the axis of rotation (central axis of the tool holder centre, shown in Fig. 3 (a)), the x and y coordinates information of the tool holder have been used to translate the centroid of the scanned probing points.

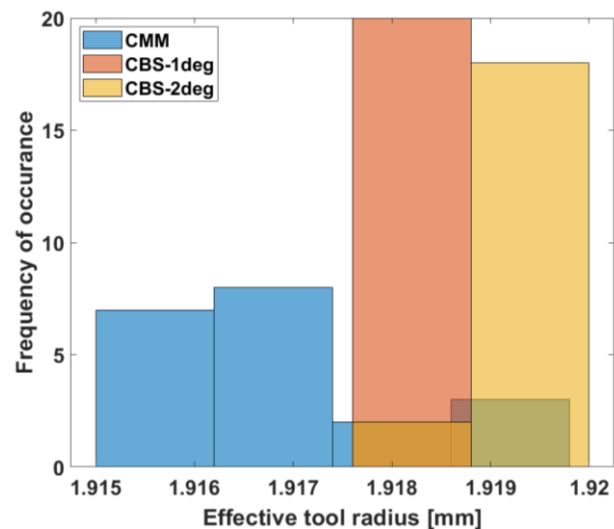


Fig. 5: Statistical distribution of the artefact's effective radius for the reference CMM and the camera-based system (CBS) at two angular resolutions labelled as CBS-1deg and CBS-2deg.

The analysis encompasses translating the centroid of the probed points by using the tool holder centroid information and detecting the local maxima (peak) corresponding to the

Tab. 2: Uncertainty budget for the effective tool radius and the runout of the camera-based optical system.

Type	One-degree angular resolution		Two-degree angular resolution	
	Effective tool radius [mm]	Runout [μm]	Effective tool radius [mm]	Runout [μm]
Mean value	1.9184 mm	26.26 μm	1.9193 mm	26.08 μm
u_{cal}	0.75 μm	0.87 μm	0.75 μm	0.87 μm
u_b	1.5 μm (1.9169 – 1.9184)	0.98 μm (25.28 – 26.26)	2.4 μm (1.9169 – 1.9193)	0.8 μm (25.28 – 26.08)
u_p	0.028 μm	0.031 μm	0.058 μm	0.08 μm
u_w	insignificant	Insignificant	Insignificant	Insignificant
$U_M(k = 2)$	3.4 μm	2.6 μm	5.0 μm	2.4 μm

four edges of the squared section of the reference artefact. The largest measured peak value corresponds to the artefact's radius while the difference between the largest and the smallest peaks is the runout.

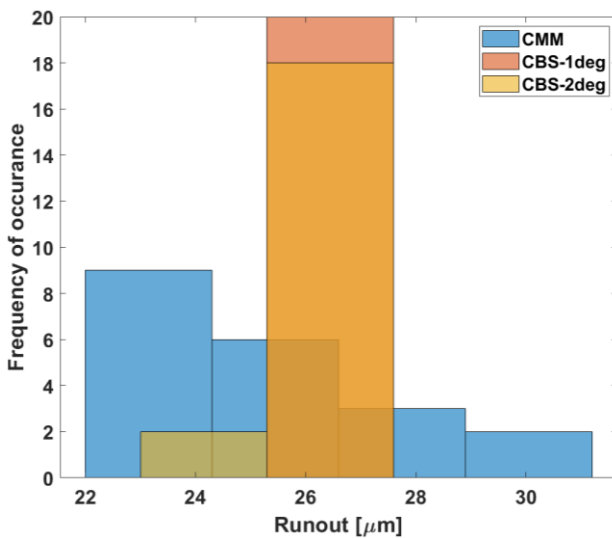


Fig. 6: Statistics of the measured runout for reference CMM and CBS for two angular resolutions.

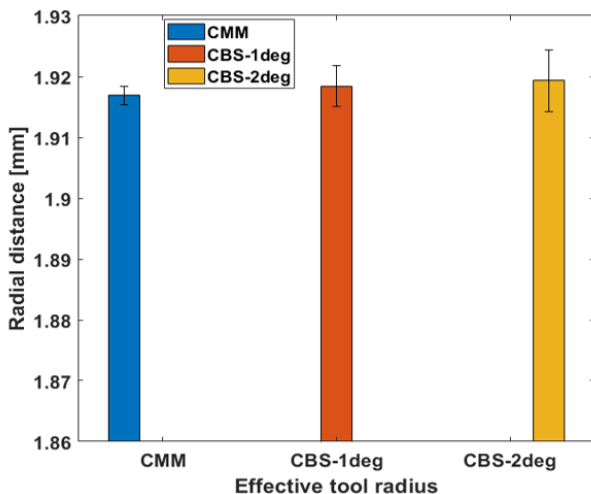


Fig. 7: A comparison of artefacts' effective radius for reference CMM and CBS for two angular resolutions labelled as CBS-1deg and CBS-2deg.

Fig. 5 shows the statistical distribution of the CMM measurements (reference) and the effective tool radius of reference artefact at one- and two-degree angular resolutions of the tool presetting optical system when the

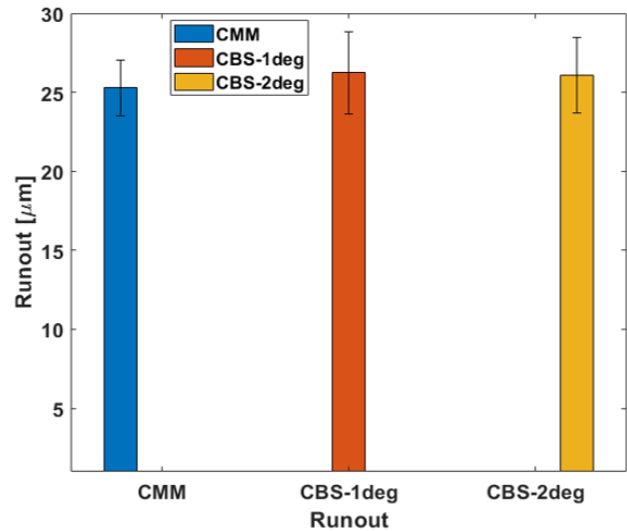


Fig. 8: A comparison of the measured runout for CMM and CBS for two different angular resolutions.

artefact was deployed in the spindle of the machine tool. The statistics of the measured runout by CMM and at two angular resolutions of the tool presetter is shown in Fig. 6. The measured results indicate that the on-machine tool presetting system has a relatively narrow spread for parameters of interests (effective tool radius and the runout) indicating the better repeatability of the optical system, specifically the spread for one-degree outcome has further been narrowed down in contrast to the normal measurement process (two-degree angular resolution).

Fig. 7 and Fig. 8 show a comparison of the measured effective radius of the artefact and the runout for CMM and the camera-based system along with the measured uncertainties. Tab. 2. provides the details of the task-specific uncertainty for the measured outcome of the camera-based optical system at normal and high angular resolutions. The one- and two-degree measurements have an expanded uncertainty of 3.4 μm and 5 μm , respectively, (95% coverage interval) in the effective tool radius while for runout, the expanded uncertainties are 2.6 μm and 2.4 μm , corresponding to one- and two-degree scenarios.

The results have demonstrated that the high angular resolution (one-degree) reduces the measurement uncertainty and enhances the instrument performance for measuring the tool geometry. Furthermore, the results of the computed tool geometry indicate that there is a systematic error (bias) by the camera-based tool presetting optical system; however, the measurement uncertainty of the optical system can be reduced significantly by

compensating this contribution which will be part of future investigations.

4 CONCLUSIONS AND FUTURE WORK

In this work, the characterization of a high-speed camera-based tool presetting system is performed for the on-machine measurement of ball end mills, following the guidelines provided in ISO 15530 Part 3. The study also investigates the high angular resolution capability of the optical instrument for tool geometry assessment. For this purpose, a ballnose shaped reference artefact is manufactured from a gauge pin and calibrated using a CMM. The task-specific uncertainty is computed, and the measured outcomes for parameters of interest (effective tool radius and runout) at normal and high angular resolutions are compared with the reference CMM measurements.

The expanded uncertainty for the measured effective radius of the artefact at one- (high resolution) and two-degree (normal) angular resolutions is 3.4 μm and 5 μm , respectively (95% coverage interval) while for runout, the expanded uncertainties are 2.6 μm and 2.4 μm , corresponding to one- and two-degree situations. Furthermore, there is a systematic error in the measurements by the tool presetter, and an investigation is ongoing to reduce this error. Future work will focus on examining the influencing factors, such as thermal and clamping errors, in the tool geometry assessment procedure.

5 ACKNOWLEDGMENTS

The authors would like to acknowledge Henrik Petersen (DTU) for manufacturing the artefact, Klaus Liltorp (DTU) for providing help with the CMM program, Ivan Nedrehagen and Øystein Svinning from Conoptica A/S for their support and valuable discussions.

6 REFERENCES

- [Bradac 2021] Bradac, C. High-resolution optical imaging and sensing using quantum emitters in hexagonal boron-nitride. *Frontiers in Physics* 2021, 9, 641341.
- [Khonina 2024] Khonina, S. N., Kazanskiy, N. L., Oseledets, I. V., Nikonov, A. V., & Butt, M. A. Synergy between artificial intelligence and hyperspectral imaging—A review. *Technologies* 2024, 12(9), 163.
- [Wang 2024] Wang, Z., Huang, M., Qian, L., Sun, Y., Lu, X., Zhao, W., ... & Zhao, Y. Near-Space Wide-Area and High-Resolution Imaging System Design and Implementation. *Sensors* 2024, 23(14), 6454.
- [Ilie 2019] Ilie, M. A., Caruntu, C., Lupu, M., Lixandru, D., Tampa, M., Georgescu, S. R., ... & Boda, D. Current and future applications of confocal laser scanning microscopy imaging in skin oncology. *Oncology letters* 2019, 17(5), 4102-4111.
- [ISO 15530-3:2011] Geometrical Product Specifications (GPS) – Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement — Part 3: Use of calibrated workpieces or standards
- [CU2 Tool Conoptica] CU2 Tool Conoptica <https://conoptica.com/products/machine-tool/cu2-tool-camera-tool-sette/>
- [Shaheen 2024] Shaheen, A., & Bissacco, G. Metrological characterisation of tool pre-setting optical systems based on 2D imaging. *Measurement*, 228, 114327.

[ISO 10360-1:2000] Geometrical Product Specifications (GPS) – Acceptance and verification tests for coordinate measuring machines (CMM) – Part 1: Vocabulary

[Savio 2002] Savio, E., Hansen, H. N., & De Chiffre, L. Approaches to the calibration of freeform artefacts on coordinate measuring machines. *CIRP Annals* 2002, 51(1), 433-436.

[ISO JCGM 100:2008] (GUM 1995 with minor corrections). Evaluation of measurement data – Guide to the expression of uncertainty in measurement

[ISO/IEC Guide 99] International vocabulary of metrology – Basic and general concepts and associated terms (VIM)

[ISO 12181-1:2011] Geometrical product specifications (GPS) — Roundness, Part 1: Vocabulary and parameters of roundness, 1990.