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TOOL WEAR ANALYSIS WITH MACHINE VISION: AN ACCURATE AND NON-CONTACT MEASUREMENT APPROACH

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Abstract: *Our work focuses on developing an optical measuring cell for controlling and measuring cutting tools in machining processes. The cell includes a camera that can move in the x and y directions, as well as a mechanism for clamping the tool. We implement an algorithm to capture and process camera images, perform edge detection, and convert coordinates and pixels to millimeters. Additionally, we incorporate automatic tool rotation for a comprehensive analysis of the cutting edges. The measurement output provides the x and y components of the cutting-edge tip, enabling precise assessment of tool wear and process optimization. This research contributes to enhancing machining technology for improved productivity and reduced costs.*

Key words: *Tool Wear Analysis, Optical Measuring Cell, Automatic Tool Rotation, Machining Process Optimization, Edge Detection Algorithm.*

1. INTRODUCTION

The progression of modern manufacturing demands investments in up-to-date enhancements and the seamless integration of state-of-the-art technologies into production procedures. Additionally, it calls for the implementation of measures that minimize human intervention. When devising a machining process involving cutting, one crucial factor influencing outcomes is tool wear, a consequence of various forces at play during the cutting procedure. Tool wear primarily results in a diminished quality of treated surfaces and subsequently reduces the precision in achieving desired workpiece dimensions [1]. To maintain high-quality processing and enhance competitiveness, minimizing the impact of tool wear is paramount. Presently, this issue is addressed by CNC operators periodically removing a specific tool from the machine and subjecting it to measurements using dedicated equipment to determine its actual size. The operator then updates the tool database with the necessary corrections, which are subsequently factored into future processing [2].

Among the most innovative tool wear monitoring applications is Tool Condition Monitoring (TCM). Excessive wear and breakage of cutting tools lead to reduced surface quality due to unevenly distributed forces during the cutting process. By employing suitable TCM techniques [3], cutting speeds can be boosted by 10-50%.

In alignment with the modernization and automation trends in contemporary production, the concept of measuring tool wear during processing itself has gained a lot of popularity. This entails placing the tool within the machine tool's vicinity where a machine vision system is stationed, allowing for automated measurement and correction without human intervention. This approach saves time, elevates automation levels, reduces the potential for human error and ensures precise processing. Leveraging statistical data and artificial intelligence, it becomes feasible to predict when a cutting tool will wear to the point of requiring replacement [4].

Broadly, TCM systems fall into two categories: direct techniques and indirect techniques [5]. Direct techniques involve the direct measurement of conditions like flank wear width, crater depth, and crater area, either offline (requiring a pause in the machining process) using tools like 3D surface profilers, microscopes or in-process using CCD cameras. In contrast, indirect TCM techniques measure various signals from the cutting process, including force, current, power, surface finish, and acoustic emissions. These measurements enable in-process assessments of tool wear. Typically, these TCM systems rely on comparing the actual process signal, acquired from sensors, with a reference signal from an optimized cutting process [6].

The implementation of these techniques has often involved technologies such as acoustic emissions, cutting force, spindle current, and vibration sensors [7]. Nevertheless, these methods have inherent limitations. Researchers are actively investigating methods to overcome these limitations by analysing various images obtained through optical sensors such as lasers, CCD and CMOS cameras, and thermal IR cameras. A diverse range of applications combining optical sensors with digital image processing and machine vision is utilized for quality control, tool wear measurement, workpiece surface assessment, and more in machining processes like milling [8].

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In our prior research endeavours, we actively contributed to the advancement of an optical monitoring system incorporated into the Sick AppStudio software package, aimed at assessing cutting tools. Within this framework, we successfully implemented this system into a prototype measuring model that exhibited robust capabilities in measuring the dimensions of rotationally-symmetric cutting tools, evaluating tool wear, and identifying potential tool damage. Our innovative approach included the construction of a measuring cell constructed from aluminum profiles, which provided secure clamping and precise positioning of the tool while allowing for automatic tool rotation through the integration of a stepper motor. Furthermore, we enhanced the system's functionality by incorporating automatic edge detection for the tool, ensuring comprehensive measurement coverage for all cutting edges. The pivotal feature of this system is its capacity to measure each facet of the tool, a task efficiently facilitated by a high-speed camera strategically positioned perpendicular to the work surface. To accommodate varying tool sizes, we also integrated adjustable guides in the x and y directions for optimal camera placement. This paper builds upon our previous research by introducing these advancements in tool rotation and automatic edge detection, significantly enhancing the system's overall capabilities.

2. PROTOTYPE MEASURING CELL

In accordance with the needs of the previously described problem, we have decided to create a prototype measuring cell with the following requirements:

- Measuring the cutting edges of cutting tools using a camera.
- Camera movement for measuring tools of different sizes.
- Automatic tool rotation for measuring all cutting edges.
- Robust framework to prevent vibrations.
- High-performance computer for rapid image analysis and presentation of results to the user.

Based on the above requirements, we have divided the design and construction of the prototype measuring cell into three parts: the fabrication of the mechanical framework, the installation of electrical components, and the installation of machine vision system components.

2.1. Mechanical part

The measuring cell's 3D model was developed with Solidworks software, aligning precisely with the application's prerequisites outlined earlier. To ensure stability and facilitate rotation along its axis, the tool had to be securely clamped in the desired position. The tool holder was crafted from aluminum, subsequently housed in a radial bearing. With conical shape, tool holder ensured steadfast tool placement and clamping, further facilitated by the radial bearing's capacity to enable the tool's free rotation for precise measurement of cutting edges.

The prototype cell mandated automatic tool rotation around its axis, a feat achieved through a stepper motor connected to the tool holder via a belt drive mechanism as shown on Fig. 1. The stepper motor's pulley boasted 16 teeth, contrasting with the 160 teeth on the tool holder's pulley.

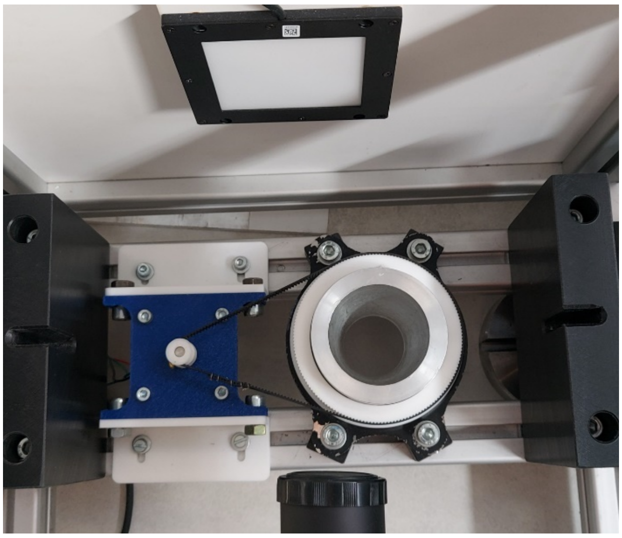

Fig. 1. Automatic tool rotation via belt drive mechanism.

For accurate measurements, a camera needed to be fixed perpendicularly to the tool, accompanied by a backlight source behind it. A solution was devised to enable the camera's movement in both the x and y directions, accommodating various tool sizes. Linear camera motion, both vertically and horizontally, relied on round guides affixed to the aluminum housing. The camera's position was regulated by polyethylene carts, produced from PETG material via 3D printing technology. Four threaded buttons were employed to release and secure the camera's position along the guide.

Incorporating a calibration grid with a 20 mm raster pattern was crucial in the prototype measuring cell's production. The primary purpose of this grid was to translate the camera's coordinate system into the tool's coordinate system. To achieve this, the calibration grid had to be designed and installed securely, preventing any unintended movement in the x and y directions or rotation. Precise alignment of the calibration grid's coordinate origin with that of the tool was imperative. Only with precise clamping and alignment could we ensure the accuracy and reproducibility of measurements.

2.2. Electrical part

In the electrical section of our setup, we utilized a 24V AC/DC converter. Linked to its output, we integrated an LED light for illuminating the tool under inspection. Additionally, our system featured the integration of a SICK SIM4000 module, which played a pivotal role in our data acquisition process. The SIM4000 module was interfaced with a NEMA23 stepper motor controlled by a DM556T stepper driver. The NEMA23 stepper motor was chosen for its exceptional precision and robust torque capabilities, which made it an ideal choice for ensuring accurate and controlled tool positioning during the measurement process, and the DM556T stepper driver ensured precise control over the motor's movements. This setup enabled us to achieve accurate and controlled tool positioning during the measurement process. Moreover, to capture high-resolution images for tool measurement, we interfaced a

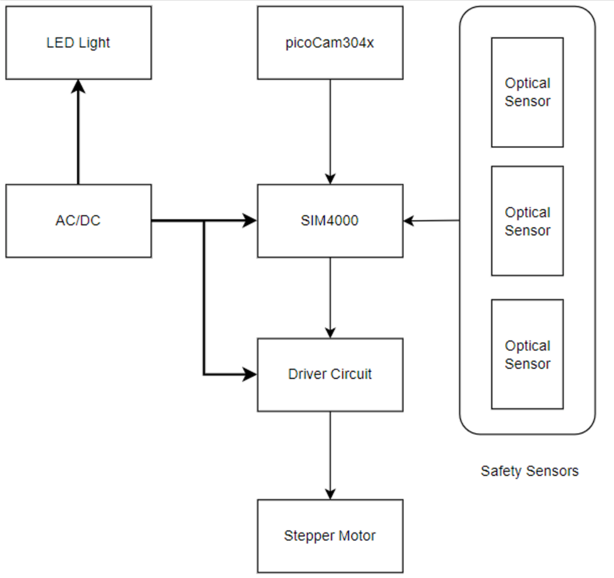

Fig. 2. Connection between components.

PicoCam304x camera with the SIM4000 module. As safety is paramount, we integrated three optical safety sensors into the electrical configuration. In Fig. 2, the connection between the components in the system is shown.

2.3. Machine vision

This chapter describes our machine vision system, designed for evaluating cutting edge wear. It prominently features the SICK picoCam304x camera. Enhanced by a telecentric lens, the camera ensures precise image capture. Integration with the SICK SIMx4000 sensor integration machine empowers machine vision algorithms for image processing and seamless cloud-based data transmission.

The heart of our machine vision system is the SICK picoCam304x camera, which stands out for its remarkable capabilities. With a resolution of 2048×2048 pixels, it delivers high-definition images that are crucial for accurate wear evaluation. Operating at a rapid 19 frames per second (fps), it can capture dynamic processes with clarity and precision. This camera's reputation for reliability and performance makes it an ideal choice for our machine vision application.

To ensure the highest level of precision in image capture, we have equipped our camera with a telecentric lens. Telecentric lenses are renowned for minimizing optical distortions, ensuring that objects are portrayed accurately in the images. This feature is especially critical when assessing wear on cutting edges, where even minor deviations can impact the evaluation's accuracy. The telecentric lens plays a pivotal role in achieving consistent and reliable results.

Seamless integration with the SICK SIM×4000 sensor integration machine further enhances our machine vision system's capabilities. The SIM×4000 is a state-of-the-art device designed to facilitate the integration of sensors and cameras into industrial processes. It provides a robust platform for deploying machine vision algorithms and handling large volumes of visual data. Our machine vision system takes advantage of cloud-based data transmission, ensuring that the results of wear evaluations are accessible and shareable in real-time.

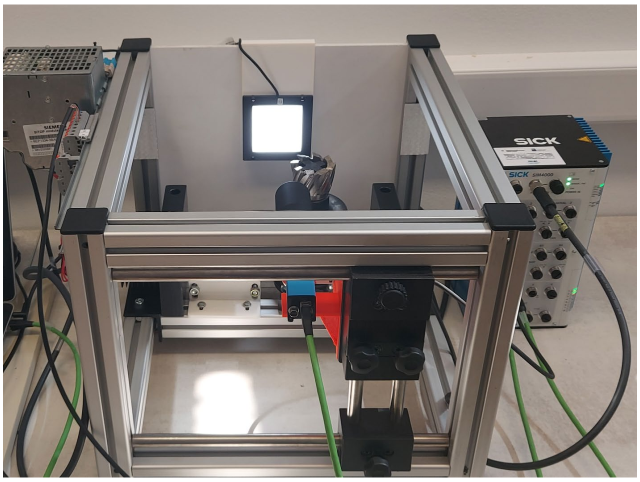

Fig. 3. Photo of the entire system.

Figure 3 shows a photo of the entire system, including mechanical frame, electrical components, and machine vision system.

3. WEAR DETECTION TOOL WITH INTEGRATED CONTROL PANEL

Tool wear assessment involves camera-based monitoring, with image data transmitted to the sensor integration system through an Ethernet connection. Our approach involves a segmented program and user interface, executed incrementally in four stages.

The initial phase centres on locating and configuring the camera's position to align with the tool clamped within the tool holder.

The subsequent stage focuses on the transformation of the camera's coordinate system into the tool's coordinate system and the determination of the image's rotation angle. For this conversion, we rely on a calibration grid discreetly placed within the tool holder.

In the third stage, we pinpoint the cutting edge of the tool and execute measurements in both the x and y directions. In order to comprehensively analyse tool wear measurements, it is essential to execute meticulous preprocessing of the captured image. Subsequently, leveraging the functions available in AppStudio, we extract relevant data concerning the x and y components of the tool's cutting edge.

The fourth and final stage entails employing a stepper motor to gradually rotate the tool. Following each rotation, we conduct measurements of the cutting edge, as outlined in the third stage.

3.1. Camera positioning

The initial phase entails defining the precise location within the captured image. This involves the utilization of both vertical and horizontal lines. Subsequently, the tool needs to be physically situated within the image's fourth quadrant, ensuring that the tool's tip aligns closely with the intersection of the two lines.

3.2. Coordinate transformation process

The second phase involves the integration of the camera and tool coordinate systems and the subsequent image rotation. To facilitate the transition from the camera's coordinate system to that of the tool, a 20 x 20 mm calibration grid was utilized. Initially, it was imperative to disengage the tool from the measuring cell and introduce the calibration grid within it. Upon activating the "Find measuring grid" button, the application captures an image of the calibration grid and identifies the intersection point where vertical and horizontal lines intersect. Following this, the application computes the rotation angle between the horizontal line within the image and the lower edge of the image. Further, it scrutinizes the image for numerical data. These numbers, inscribed on the grid, denote the x and y distances of the intersection on the calibration grid, positioned just beneath the numbers. The upper figure signifies the x-distance, while the lower one represents the y-distance from the intersection, with reference to the tool's coordinate system origin. The application conducts an assessment within the image to determine whether the numbers are situated to the right or left of the identified vertical line. Accordingly, it aligns the coordinate system of the image's intersection with that of the calibration grid. As the second phase culminates, the application rotates the image to orient the horizontal line discovered parallel to both the top and bottom edges of the image, as depicted in Fig. 4.

3.3. Identifying and measuring tool edges

The main objective of the third step is to find the cutting edge of the tool and the point with the largest diameter. Firstly, it was necessary to remove the calibration grid from the cell and re-install the tool in it. After the image of the tool is taken, image is rotated by the angle calculated in the second step described in chapter 3.2. The application then draws a small rectangle on the image, which can be seen in the Fig. 6. Within this rectangle, each point of the cutting edge of the tool is then located. Due to the use of background lighting, which provides an intense contrast between the background and the observed object, it is possible to easily determine the cutting edge of the tool, which is black in the image. After successfully finding the cutting edge points, the application determines the point on the tool with the smallest x coordinate. This is the point that represents the maximum diameter of the tool.

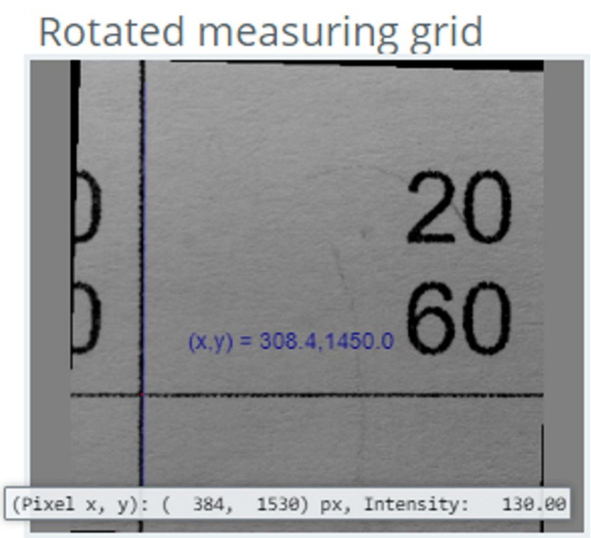

Fig. 4. Coordinate transformation process.

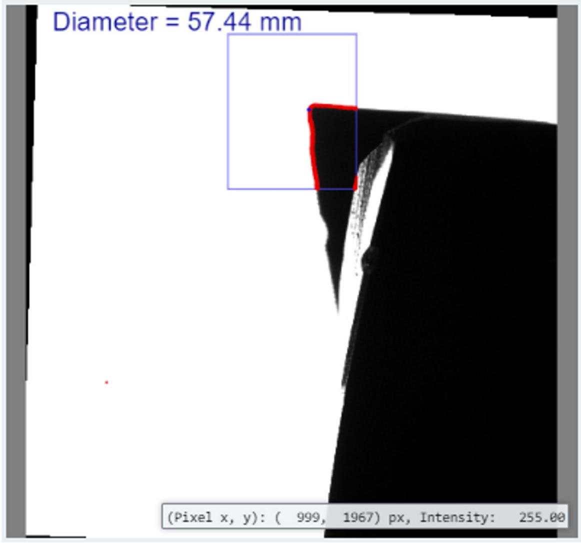

Fig. 5. Identifying and measuring tool edge.

The resolution of the measurement system can be calculated from the resolution of the camera and the field of view of the lens. The resolution of the camera we used in the system is 2048px × 2048px. The field of view of the lens is 27 mm × 27 mm. Equation (1) shows the calculation of the theoretical resolution of the developed measurement system.

$$Res = \frac{27\ mm}{2048\ px} = 0.01318\ \frac{mm}{px} = 13.18\ \frac{\mu m}{px} \quad (1)$$

We can see that the resolution of the developed system is 13.18 μm/px. After application calculates the tool diameter, the following details are displayed on the screen: the found cutting edge, the point with the largest diameter and calculated diameter. Figure 5 shows the found cutting edge of the tool and the calculated diameter.

3.4. Measuring All Cutting Edges Through Tool Rotation

After successful measurement of the first cutting edge of the tool, the value of the found diameter is displayed on the screen. The tool rotation is then performed. As part of our research, we decided to rotate the tool through an angle of 4.5 degrees and measure the diameter of the bore after each measurement. In order to rotate the tool around its axis, we needed 80 measurements of the tool. After each measurement, the application rotates the tool again, finds the cutting edge of the tool, calculates the diameter, and displays the measurement values on the screen.

3.5. Graphical user interface

The HTML programming language was employed to develop the application's graphical user interface. This interface facilitates user interaction with the measurement system, allowing access by inputting the accurate IP address into a web browser on any device such as a computer, tablet, or smartphone, as long as it is connected to the same network as the SIMx4000 sensor integration device.

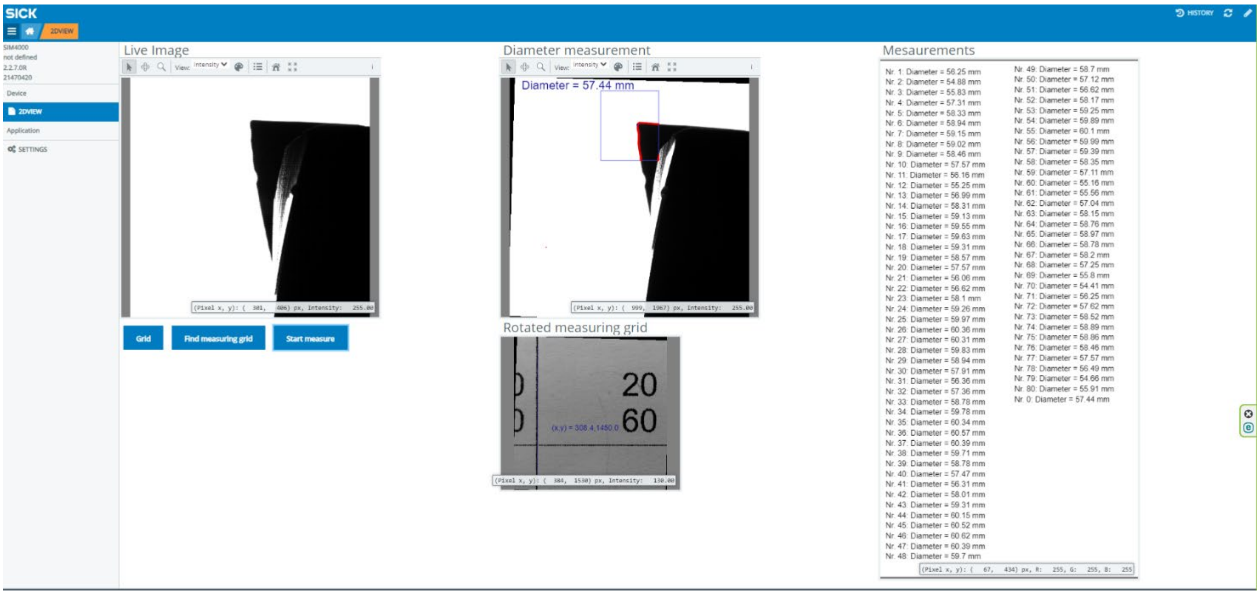

Fig. 6. Graphical user interface.

The user interface consists of the following components:

- 3 buttons for interaction between user and measuring system.
- 4 images for analysing results.

Figure 6 shows the graphical user interface of our application.

The image on the left labeled "Live Image" shows the live image taken from the camera. By using the button marked "Grid" it is possible to draw a parallel and vertical line on the image for positioning the camera in the first step of the tool measurement process, which we described in chapter 3.1.

The image labelled "Rotated measuring grid" shows a rotated image of the calibration grid and the point of intersection of the lines on the calibration grid in pixels. A detailed description of the acquisition of this image is described in chapter 3.2.

The image labelled "Rotated measuring grid" shows a rotated image of the calibration grid and the point of intersection of the lines on the calibration grid in pixels. A detailed description of the acquisition of this image is described in section 3.2. The developed application is using this image to connect the coordinate system of the camera with the coordinate system of the tool after pressing the button "Find measuring grid".

After successfully positioning the camera and capturing the calibration grid, the system is ready to measure the cutting edge of the tool. Pressing the "Start measure" button starts the measurements when the tool is re-inserted into the measuring cell. The application first captures an image of the tool, then finds the cutting edge and the point with the largest diameter as described in chapter 3.3. All elements are shown in the image marked "Diameter measurement", where the already calculated diameter of the tool is also displayed.

After a successful measurement of the cutting edge, the serial number of the measurement and the calculated diameter are displayed on the right image labelled "Measurement". After that, tool rotation is performed, where the tool is rotated by 4.5 degrees using a stepper motor. The measurement process is repeated, and the new measurement value is written on the image labelled "Measurement". The process is repeated 80 times until the system measures the entire tool.

4. RESULTS

This chapter presents the results of our study, which focuses on the measurement of eight cutting edges on the tool. The results are displayed graphically and show the maximum diameter on the tool in millimeters for each measurement.

Figure 7 shows a graph where we can see the results when using 80 measurements for the whole herd. The tool was rotated by an angle of 4.5 degrees after each measurement.

From the results, 8 cutting edges on the tool can be discerned. Figure 8 shows a graph with the results when using 160 measurements in one rotation of the tool.

From the results in Fig. 8, the 8 cutting edges on the tool can be clearly seen. In this case, the points with the largest diameters are much closer together where the camera detected the cutting edge of the tool. Compared to the results when using 80 measurements, the largest diameters of each cutting edge can be determined more precisely.

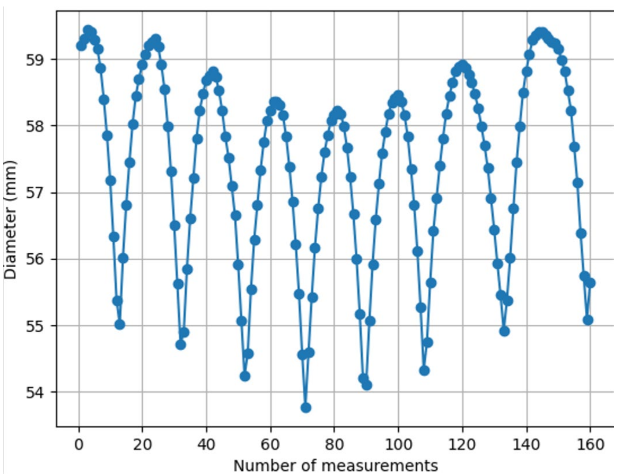

Fig. 7. Results from 80 measurements.

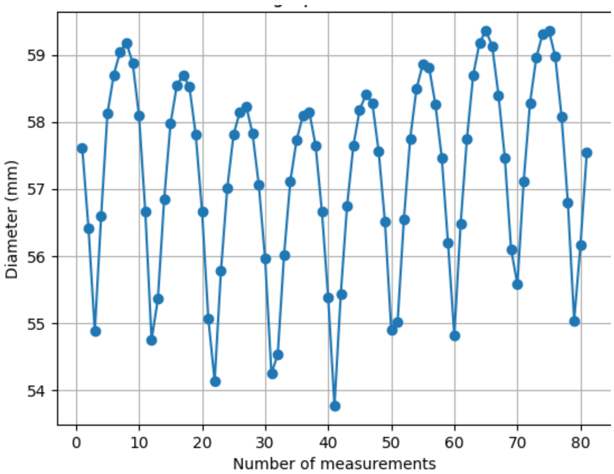

Fig. 8. Results from 160 measurements.

Table 1

Results of measuring the cutting edges of the tool

Measuring system		SICK 80	SICK 160	Zoller "Smile 420"	Caliper
Measured diameter [mm]	D1	59.18	59.44	59.580	59.34
	D2	59.29	59.31	59.460	59.25
	D3	58.78	58.81	58.921	58.75
	D4	58.32	58.36	58.543	58.63
	D5	58.15	58.23	58.323	58.15
	D6	58.38	58.46	58.483	58.35
	D7	58.80	58.99	58.920	58.85
	D8	59.39	59.41	59.432	59.42
Error [%]		0.29	0.17	Reference	0.31

The results obtained through the utilization of our newly devised measuring system were subjected to a comparative analysis against measurements carried out with a caliper and measurements performed using the Zoller "Smile 420" optical measurement system.

Measurements were made for all 8 cutting edges of the tool. The results together with the calculated errors of the selected measuring systems are shown in Table 1. Here we used the Zoller "Smile 420" measuring system as a reference, which enables more accurate measurements than a caliper.

The measured diameters of each cutting edge marked D1–D8 on the tool are shown in the table. The label "SICK 80" shows the results obtained using the developed system at 80 measurements for one revolution of the tool. The label "SICK 160" shows the results obtained from 160 measurements for one tool revolution.

The best results were obtained when using our system at 160 measurements, as the error compared to the Zoller "Smile 420" system was the smallest and amounted to 0.17%. The worst results were obtained using a calliper, where the error was 0.31%.

5. CONCLUSIONS

In the context of modernizing manufacturing operations and aligning with the principles of Industry 4.0 and the upcoming Industry 5.0, achieving higher productivity while minimizing tool wear and damage is imperative to sustain competitiveness in the market.

The optical measuring cell we have developed for tool wear control fulfills the fundamental requirements for tool wear monitoring, allowing for corrective actions on CNC machines. However, it is essential to acknowledge the limitations of our system, particularly in terms of measurement accuracy for severe tool wear. Nevertheless, the camera's resolution proves to be adequate for tool condition assessment through machine vision.

The optical tool wear monitoring system also presents opportunities for further enhancements to the existing measuring cell. Implementing motor drives for camera movement in the x and y directions, along with the use of limit switches, could simplify the tool's coordinate system determination, eliminating the need for the current calibration grid.

Our focus will be on advancing this prototype system with increased automation, including automated camera movements. These enhancements aim to streamline the measurement process for operators. This system serves as the foundation for developing a cognitive cyber-physical control system for real-time tool condition monitoring during machining. Future plans include incorporating this system into a practical CNC machining cell. The integration of a machine vision system for tool wear control into CNC machining processes will require linking the optical system with the CNC machine controller and installing the measuring system within the CNC machine.

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