TOOL WEAR MEASUREMENT USING MACHINE VISION SYSTEM

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Abstract: *When designing a machining process with cutting, one of the key influencing factors is tool wear, which occurs as a result of the action of various forces during the machining process. In accordance with the modernization of modern production, our work includes the development of an optical measuring cell for the control and measurement of cutting tools. This covers the planning, design and manufacture of the measuring cell, which enables the attachment of the camera and its movement in the x and y directions, as well as the appropriate clamping of the tool. It also includes the implementation of the algorithm for capturing the image from the camera and its processing with edge detection, converting the camera's coordinate system into the tool's coordinate system, and converting pixels to millimetres. The final output parameter of the measurement is the value of the x and y components of the tip of the cutting edge.*

Key words: *tool wear, machine vision, camera, SICK AppStudio, measurement system*

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1. Introduction

The modernization of modern production dictates investments in new upgrades and the integration of advanced technologies into production processes, as well as the introduction of measures with as little human intervention as possible. When designing a machining process with cutting, one of the key influencing factors is tool wear, which occurs as a result of the action of various forces during the cutting process. The result of tool wear is first of all a reduced quality of the treated surfaces, and then a lower accuracy of achieving the desired dimensions of the workpiece (Teti et al., 2010). In order to ensure high-quality processing and thus greater competitiveness, we want the impact of tool wear to be as small as possible. Nowadays, the problem is solved by the CNC operator removing a specific tool from the machine tool every now and then, taking the tool to a measuring device, where the actual size of the tool is measured. Operator then updates the tool database with corrections and these tool corrections are then taken into account in further processing (Mohanraj et al., 2020).

One of the most innovative monitoring applications is Tool condition monitoring (TCM), which is inevitable for reducing machine downtime (Denkena et al. 2009). One of the main causes of downtime is excessive wear and breakage of cutting tools. Damaged tool can therefore decrease quality of machined surface, due to unevenly distributed forces during cutting process. With appropriate TCM techniques (Rehorn et al., 2005) cutting speeds can be increased by 10-50 %.

In accordance with the modernization and automation of modern production, the idea arises that tool wear could be measured directly during the processing itself. The tool would be placed in the area inside the machine tool where the machine vision system is located and automatic measurement and correction of the tool would be carried out without human intervention. This would save time, achieve a higher level of automation, reduce the possible influence of the human factor and ensure accurate processing. Based on statistical data and artificial intelligence, it would also be possible to predict in advance when cutting tool will be so worn that it should be replaced (Dutta et al., 2013).

Basically, TCM systems can be divided into two groups: direct techniques and indirect techniques (Li & Tian, 2013). In the direct techniques conditions such as flank wear width, crater depth and crater area are measured directly in off-line method (machining process must be stopped during measurement) using 3D surface profiler, electron microscope or optical microscope. Previously mentioned condition can also be measured using in-process methods (it does not require stoppage of the machining process) with CCD camera. In indirect TCM techniques the following signals of cutting process are measured: force, current, power, surface finish, acoustic emission, etc. Measurement of those signals allow conclusions to be drawn about the degree of tool wear using in-process methods. These TCM systems are typically based on comparing a reference signal from an optimized cutting process to the actual process signal acquired from previously mentioned sensors (Wang & Gao, 2006).

These techniques have been implemented mainly by using various technologies such as acoustic emissions, cutting force, spindle current and vibration sensors (Pfeifer & Wiegers, 2000).

However, there are also some very serious limitations when using these methods. To overcome these limitations, much research is currently being conducted to determine the degree of tool wear by analysing different images acquired using different optical sensors such as lasers, CCD and CMOS cameras, and thermal IR cameras. There are a wide range of applications that combine optical sensors with digital image processing and machine vision which are used for quality control, tool wear measurement, workpiece surface measurement, etc. in machining processes such as milling (Župerl et al., 2022).

As part of the work, we were involved in the development of an optical system for the control of cutting tools in the Sick AppStudio software package and implemented it in a prototype measuring model, which enables reliable measurements of the dimensions of rotationally-symmetric cutting tools, tool wear and the detection of possible damage to the tool. The measuring cell, consisting of aluminium profiles, allows the tool to be clamped and fixed in the desired place, while allowing the tool to rotate around its axis, so that each tile on the tool can be measured by rotating the tool. A high-speed camera with appropriate lighting is fixed perpendicular to the work plate. The position of the camera can be set according to the size of the tool we want to measure by moving the camera via guides in the x and y directions.

2. Measuring cell

It was necessary to design, draw and manufacture a measuring cell that would allow the camera to be attached and moved in the x and y directions. With this, we were able to cover the entire measuring range and measure various tools regardless of their size. It was also necessary to find a solution for clamping the tool, which will ensure that it is always fixed at the same, precisely determined place, which we determined according to the focal length of the camera. At the same time, it was necessary to allow the tool to rotate around its axis in order to be able to measure each individual cutting edge on the tool. The focal length of the camera lens had to be taken into account in order to obtain a sufficiently high-quality image, which will then be suitable for further processing. Since the measurement of tool wear with the help of a camera is also significantly affected by light disturbances from the surroundings, it was necessary to ensure constant lighting and to prevent the penetration of external light into the measuring cell.

2.1 Design of the measuring cell

The 3D model of the measuring cell was designed in the Solidworks software tool based on the requirements dictated by the application and described in the previous paragraph. The tool had to be clamped and fixed in the desired position, while allowing it to rotate on its axis, which would allow each cutting edge on the tool to be measured. It was necessary to attach a camera perpendicular to the tool, and to install a backlight light behind the tool. We had to find a solution so that the camera can move in the x and y directions in order to measure different tools of different sizes and make sure that the distance between the camera and the cutting edge of the tool is a constant focus distance. The 3D model of the measuring cell that was developed is shown in Fig. 1.

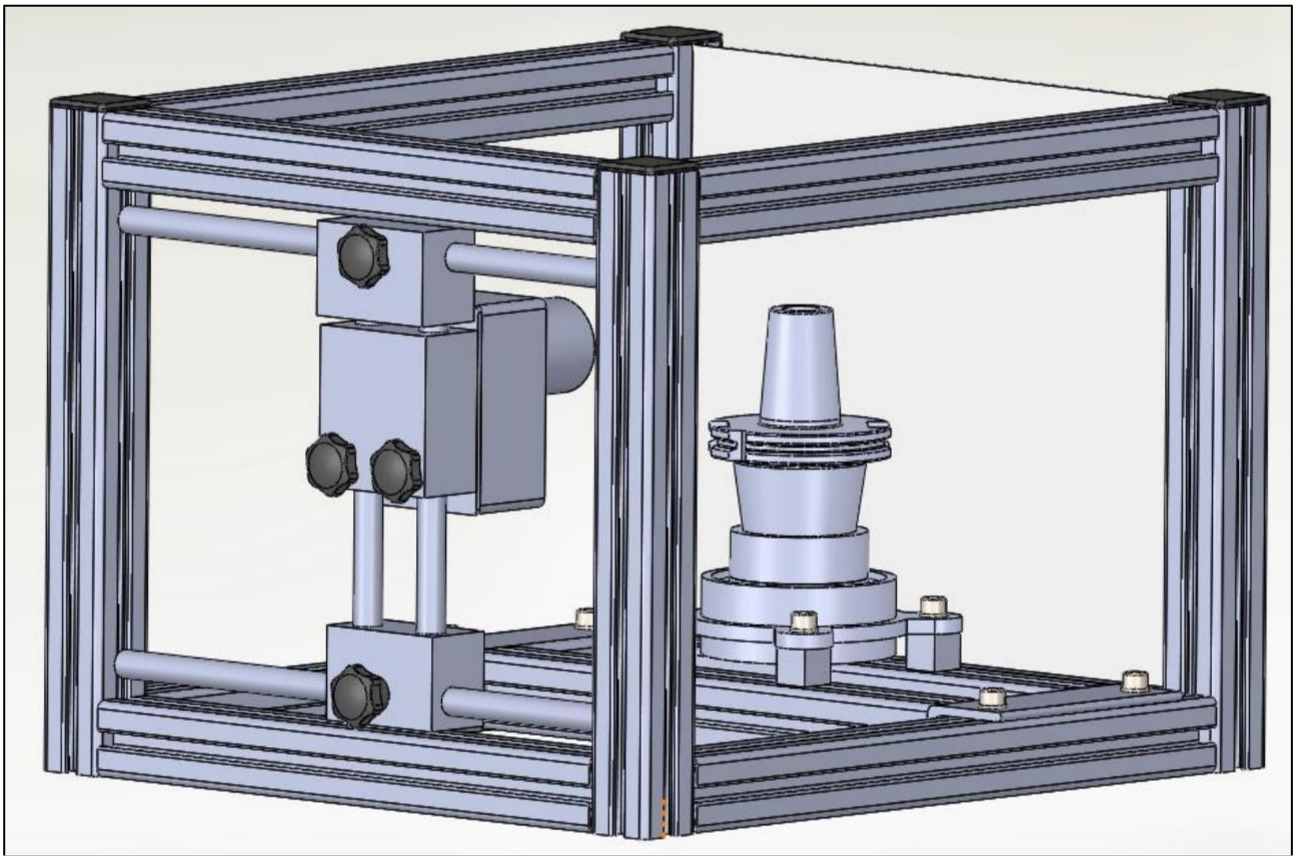

Fig. 1. 3D model of the measuring cell

2.2 Tool holder design

For ease of machining, the tool holder was made of aluminium and was then inserted into a radial bearing with housing. The tool holder is tapered for the SK 50 taper, which enables stable positioning and clamping of the tool. It is mounted with a radial bearing and allows the tool to rotate freely in order to be able to measure each cutting edge on the tool.

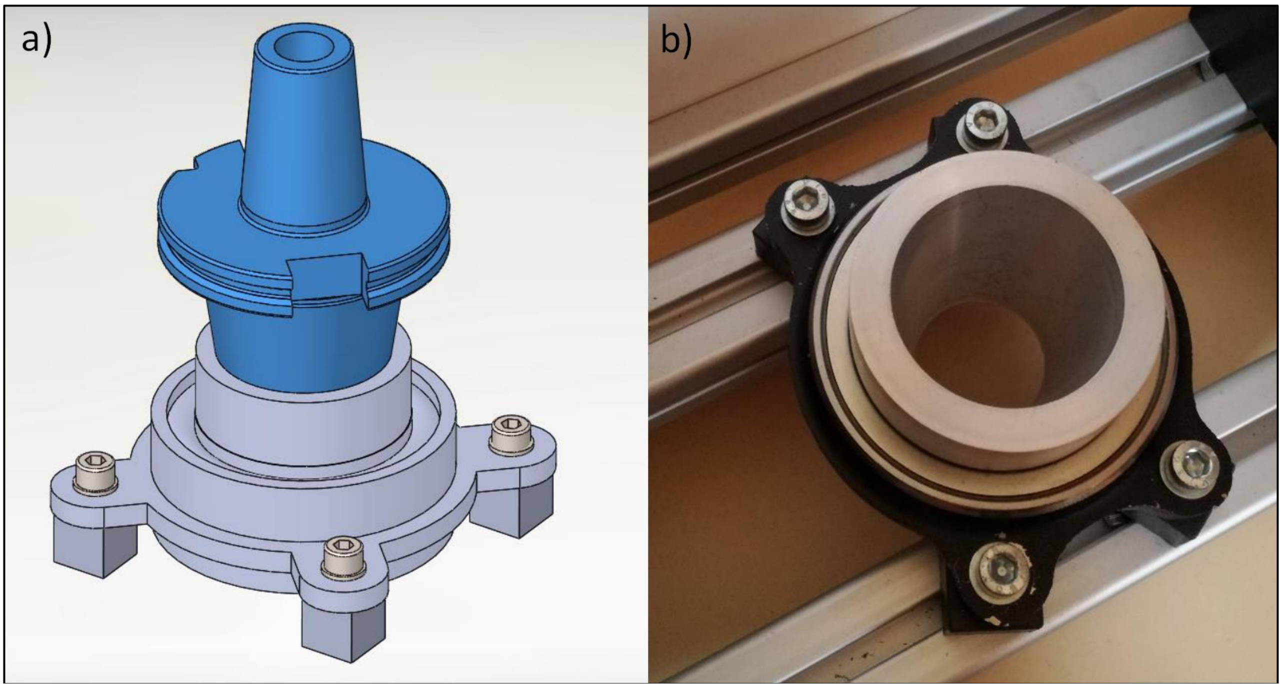

Fig. 2. a) 3D model of tool holder, b) Actual implementation of tool holder

The movement of the tool holder is possible in the x direction via the four screws with which the bearing housing is attached to the aluminium profiles, or in the y direction by moving two aluminium profiles along the T-groove. In principle there is no need to move the tool, as this position can be set via camera movement, where the position can be set more precisely and continuously.

We determined the position of the tool in the z direction at the beginning and blocked it. The 3D model of the tool holder is shown in Fig. 2a. The actual implementation of the clamping in the measuring cell is shown in Figure 2b.

2.3 Camera mount design

The linear movement of the camera in the vertical and horizontal directions was implemented via round guides, which were attached to the aluminum housing. The position of the camera is determined using polyethylene carts, which were made from PETG material using 3D printer. Releasing and fixing the camera position is set via four threaded buttons that are screwed to the guide in the position in which we want to fix the camera position. With this, we ensured accurate and consistent changes in the camera position. To ensure a constant focus distance, the movement in the z direction is disabled. The model of the camera attachment is shown in Fig. 3, where the two possible directions in which the camera can be moved are indicated.

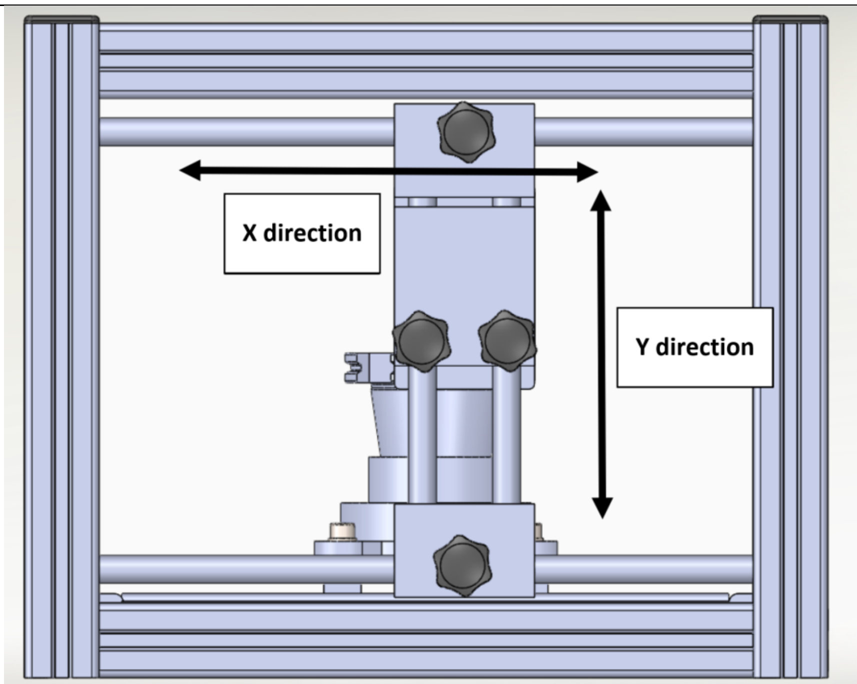

Fig. 3. Model of the camera attachment

2.4 Calibration grid installation

The main purpose of using the calibration grid is to convert the camera coordinate system into the tool coordinate system. We had to install the calibration grid and prevent movement in the x and y directions and its rotation. It was also necessary to align the coordinate origin of the calibration grid with the coordinate origin of the tool. We were able to ensure accurate measurements and their reproducibility only with high-quality clamping.

3. Machine vision system

This chapter will present the hardware and software used in the development of a machine vision system for determining cutting edge wear.

3.1 Hardware

The built system consisted of the following hardware:

- Camera SICK picoCam304x
- Sensor integration machine SICK SIMx4000
- 24 V power supply
- LED backlight
- Telecentric lens

The tool's image will be captured by the SICK camera, which has a resolution of 2048 px x 2048 px and enables the capture of images at a speed of 19 fps. The camera will be fitted with a telecentric lens that allows for 27mm x 27mm image capture.

The camera will be connected to the SICK SIMx4000 sensor integration machine via an Ethernet communication interface. All machine vision algorithms will be implemented inside the SICK SIMx4000, and at the same time the machine will also take care of sending the data to online cloud, which can then be accessed via a personal computer, tablet or phone. The 24 V power supply will provide power for the following components: the camera, the sensor integration machine, and the LED backlight.

3.2 Software

SICK AppStudio software tool was used to create an application for determining the wear of cutting edges. SICK AppStudio is used for developing customer-specific applications on programmable SICK devices. It includes Flow Editor and Lua script programming technologies for creation of sensor applications.

As part of the research, we used SICK AppStudio to create an application that took care of capturing the image via the camera, processing the image, calculating the diameter of the tool and sending the data to the cloud. At the same time, as part of the development of the application, we also created a user interface that will allow users to perform measurements more easily in the measuring cell. The developed application will be described in more detail in the next chapter.

4. Application for determining tool wear

Tool wear measurement is monitored by a camera, which transmits the captured image to the sensor integration machine via an Ethernet connection. We have divided the program and user interface into three sections, which are implemented step by step. The first part consists of finding and setting the position of the camera according to the tool that is clamped in the tool holder. Vertical and horizontal lines are helpful in this step. We locate the tip of the machining tool at the intersection of these two lines. At this point, we fix the position of the camera via threaded buttons.

The second part consists of converting the camera coordinate system to the tool coordinate system and finding the rotation angle of the image. A calibration grid with a 20-mm grid, which was installed at the place where of tool holder, was used for coordinate system conversion.

The third part consists of finding the cutting edge of the tool and performing measurements of the cutting edge in the x and y directions. To analyse the measurement of tool wear, it was necessary to properly pre-process the captured image and then, using the functions included in AppStudio, obtain information about the x and y components of the tool cutting edge.

4.1 Step 1: Positioning the camera

In the first step, it is necessary to determine the area in which the captured image should be located. This was done by using a vertical and horizontal line as shown in Fig. 4. It is then necessary to physically position the tool in the 4th quadrant of the image, so that the tip of the tool is almost exactly at the intersection of the two lines. To draw a line in the horizontal and vertical directions, it was necessary to determine the starting and ending points, which are specified in the number of pixels. Here, the first component represents the number of pixels in the x direction and the second in the y direction.

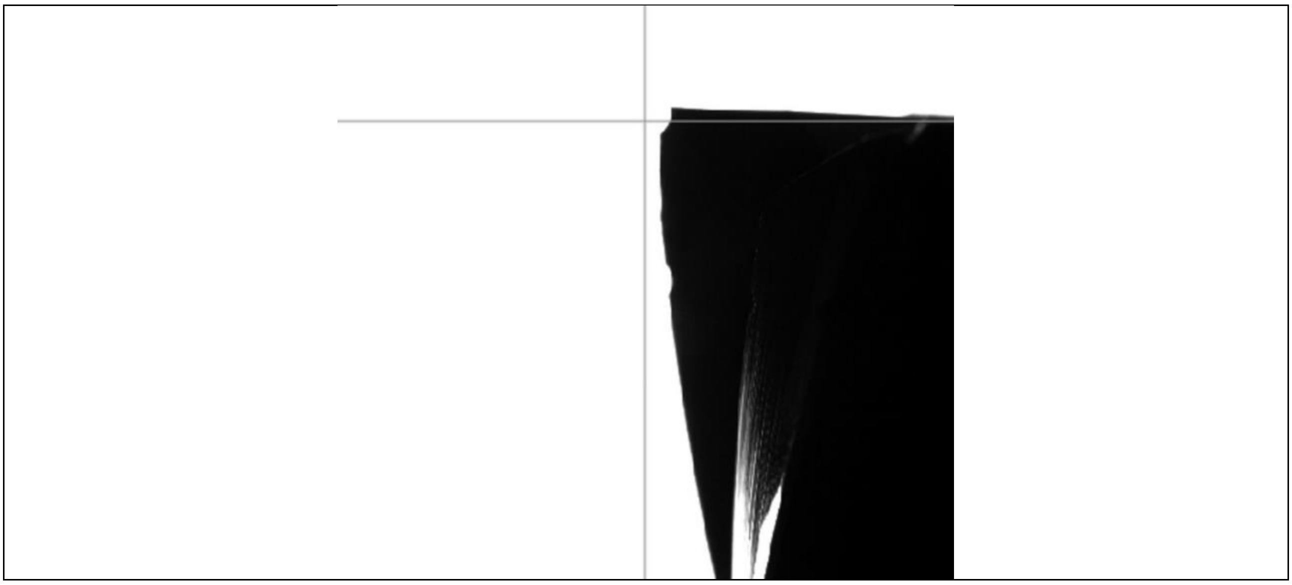

Fig. 4. First step of tool measurement procedure

4.2 Step 2: Converting the coordinate system

The second step consists of linking the coordinate systems of the camera and the tool and rotating the image. To convert the camera's coordinate system into the tool's coordinate system, we used a 20 mm x 20 mm calibration grid. Firstly, it was necessary to remove the tool from the measuring cell and install the mentioned calibration grid inside it. After pressing the "Find measuring grid" button, the application captures the image of the calibration grid and finds the intersection of the vertical and horizontal lines in the image. The application then finds the angle of rotation between the horizontal line in the image and the bottom edge of the image.

The coordinates of the intersection of the found lines and the angle of rotation are displayed on the screen, as shown in Fig. 5a. The application then searches for any numbers in the image. The numbers written on the grid represent the x and y distances of the intersection on the calibration grid, located to the right below the numbers. The upper number represents the x and the lower y distance of the intersection based on tool coordinate system origin. The application in the image checks whether the numbers are located on the right or on the left side of the found vertical line and accordingly connects the coordinate system of the intersection in the image with the coordinate system on the calibration grid. At the end of the second step, the application rotates the image so that the horizontal line found is parallel to the bottom and top edges of the image, as shown in Fig. 5b.

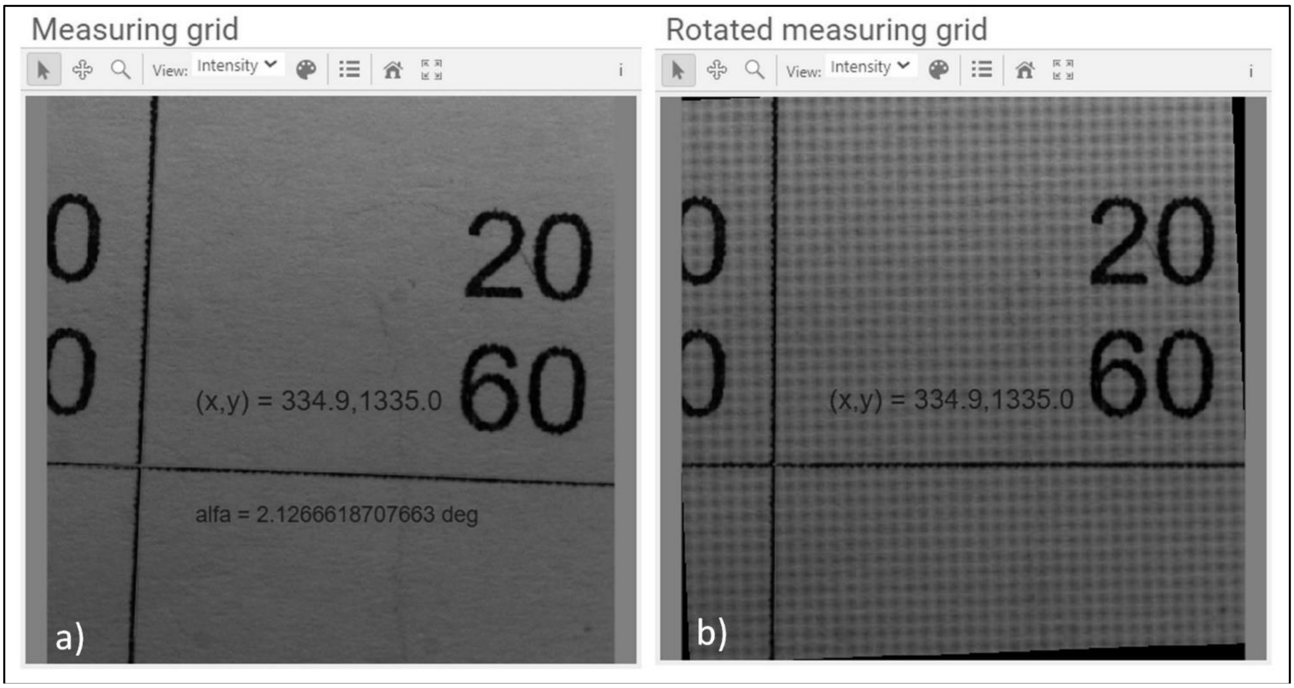

Fig. 5. Second step of tool measurement procedure

4.3 Step 3: Measurement the cutting 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. The tool must be rotated so that the first cutting edge of the tool is clearly visible in the image. After pressing the "Measure diameter" button, the application measures the diameter of the tool. When the button is pressed, the image is rotated by the angle calculated in the second step described in chapter 4.2. 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. The tool diameter is calculated using equation (1):

$$D = 2 \cdot (r_0 \pm k \cdot |x_1 - x_0|) \quad (1)$$

where D is the largest diameter (expressed in mm) of the cutting edge of the tool, r_0 is the distance in the x direction between the vertical line from step 2 and the centre of the tool holder (expressed in mm), k is the resolution of the measurement system, x_0 is the x coordinate on the image (expressed in px) of the intersection of the lines from step 2 and x_1 is the x coordinate on the image (expressed in px) of the point on the tool with the largest diameter.

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 x 2048px. The field of view of the lens is 27 mm x 27 mm. Equation 2 shows the calculation of the resolution of the used measurement system:

$$k = FOV_x / r_c = 27\, mm / 2048\, px = 0.01318\, mm/px = 13.18\, \mu m/px \quad (2)$$

where FOV_x is the field of view of the lens in the horizontal direction and r_c is the resolution of the camera in the horizontal direction. We can see that the resolution of the developed system is 13,18 µm/px.

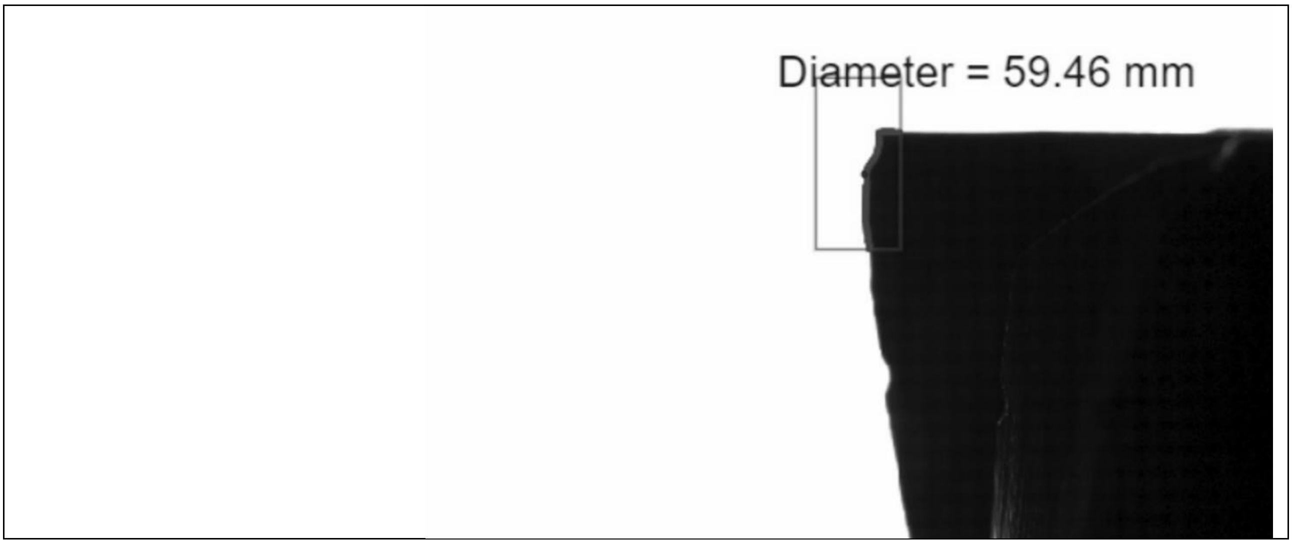

Fig. 6. Third step of tool measurement procedure

Using equations 1 and 2, the application calculates the tool diameter. Then the application draws on the screen the found cutting edge, the point with the largest diameter and prints the calculated diameter of the tool in mm as shown in Fig. 6.

4.4 Application control panel

The application control panel was created using the html programming language. The control panel enables the connection between the user and the measuring system. The control panel can be accessed by entering the correct IP address in a browser on a computer, tablet or phone when the device is connected to the same network as the SIMx4000 sensor integration machine.

The control panel of the application consists of four images, three buttons and instructions for performing measurements. It is shown in Fig. 7.

The left image named "Live image" shows the live image captured by the camera. By pressing the "Grid" button, the vertical and horizontal lines can be turned on or off.

The upper middle image named "Measuring grid" shows the image of the calibration grid obtained by pressing the button "Find measuring grid" after placing the calibration grid in the measuring cell. The coordinates of the found intersection point and the image rotation angle are displayed on the image. In the middle image below, with the name "Rotated measuring grid", a rotated image of the calibration grid and the coordinates of the found intersection are shown.

The right image named "Diameter measurement" shows the image of the tool when the "Measure diameter" button is pressed after calibration grid was successfully found in the previous step and the tool was placed back into the measuring cell. The image also shows the calculated diameter in mm.

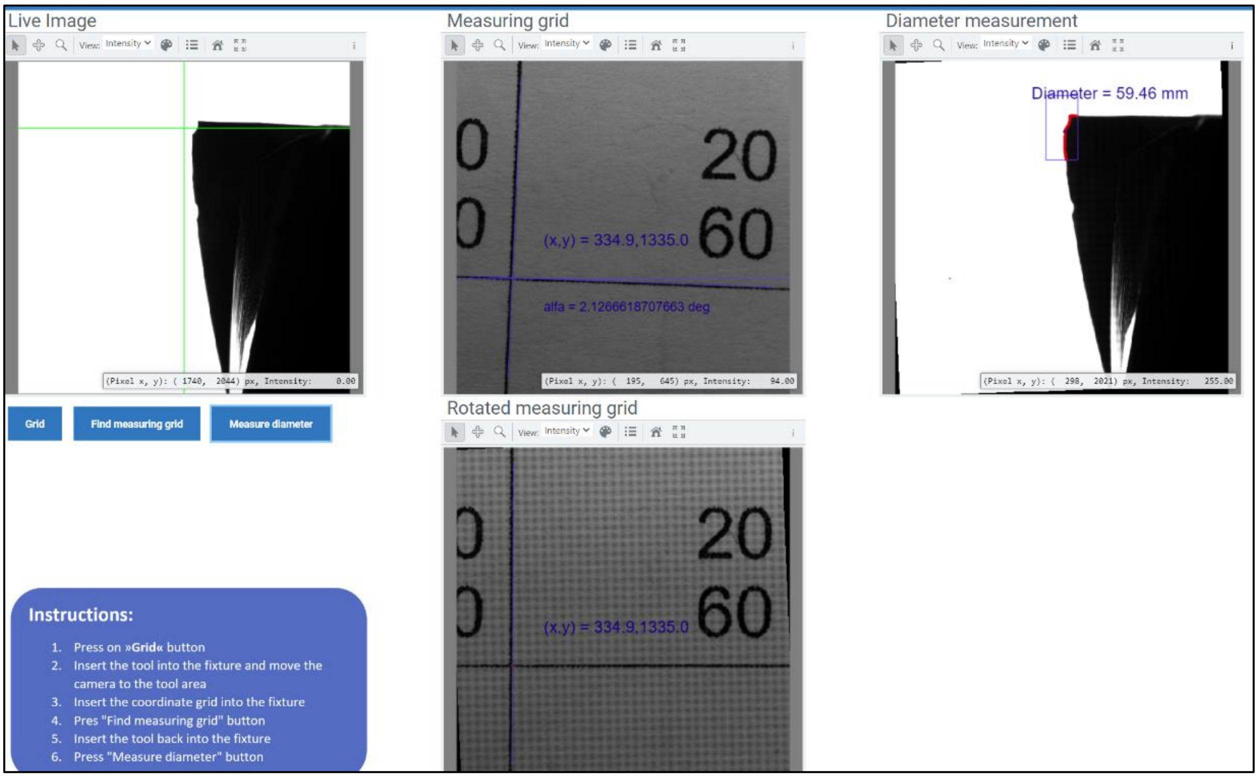

Fig. 7. Application control panel

In order to successfully measure all the cutting edges of the tool, it was necessary to manually rotate the tool and measure each cutting edge separately by pressing the "Measure diameter" button.

5. Results

The measurement results obtained with the developed measuring system were compared with measurements using a caliper and with measurements on the Zoller “smile 420” optical measuring system (***).

We compared the results of the measurements of the four cutting edges of the tool and compared the results when using three different measurement systems. As a reference, we used the Zoller measuring system, which allows a more accurate measurement than caliper. The results of the measurements are shown in Table 1.

Measuring system	Measured diameter [mm]				Average [mm]	Error [%]
Zoller "smile 420"	59.580	59.576	59.572	59.55	59.570	Reference
Caliper	59.45	59.40	59.53	59.38	59.44	0.219 %
Our system	59.552	59.522	59.542	59.467	59.521	0.082 %

Tab. 1. Results of measurements

From the results, we can see that using the developed measuring system we achieved better results than using a calliper. The relative measurement error of the constructed system compared to the Zoller measuring system was 0.082%. The relative error when using calliper was 0.219%, which is 2.6 times more than the error of our developed system.

6. Conclusion

When we talk about the modernization of production and the fulfilment of the requirements dictated by Industry 4.0 and Industry 5.0, which is fast approaching, the need to achieve higher productivity, reducing wear and damage on the tool are crucial for ensuring competitiveness on the market.

The test optical measuring cell for tool wear control that we have developed meets all the needs for tool wear control, based on which we can perform tool correction on a CNC machine. Regardless, it has certain drawbacks and allows for additional expansions and upgrades. Based on the measurement accuracy calculation we performed in Chapter 5, we found that our system does not give satisfactory results in terms of measurement accuracy for serious tool wear measurements. However, the resolution of the camera is quite sufficient for the needs of testing the tool condition with the help of machine vision.

The optical tool wear monitoring system also offers other options for upgrading the existing measuring cell. Using a motor drive to move the camera in the x and y directions and using limit switches would simplify the determination of the tool coordinate system and the conversion of the camera coordinate system to the tool coordinate system, since the position in which both limit switches have a signal would represent the reference position. Therefore, there would be no need to use a calibration grid, as we did now. With each movement of the camera, system would know exactly where it is located. Also, with the motor drive of the tool rotation, the measuring cell would be fully automated and there would be no need for human intervention in the measuring cell for each individual measurement.

The implementation of a machine vision system to control tool wear in the machining process on a CNC machine would also require the connection of the optical system to the CNC machine controller and the installation of measuring system in the CNC machine itself.

Future activities will be carried out to evolve the presented tool wear measurement system with automation, such as automatic camera movement and automatic tool rotation, which will simplify and speed up the measurement process for the operator. The presented system will serve as a basis for the creation of a cognitive cyber-physical control system for controlling the state of the tool during the machining process, which we want to develop in the future.

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