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HUMAN VISUAL MODEL-BASED TECHNOLOGY: MEASURING THE GEOMETRIC PARAMETERS OF MICROINSTRUMENT

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In the paper, a scheme of an optical microscope which includes a special bitelecentric optical system for the formation of a diode support and a telecentric objective for capturing the image has been designed and implemented. The use of such system makes it possible to reduce the diffraction effects at the edges of the shadow structure and to measure (using the microscope) the main parameters of a cutting microinstrument: its protrusion and diameter. An algorithm for modeling the two main visual channels of the human eye was developed. It allowed rapid detection of spatial-temporal processes and noise, and provided measuring the cutting edge contour of the instrument with a subpixel error (up to 0.01 pixel) and determining the dimensions of the cutting tool with an error of 0.5 μm.

Keywords: telecentric objective, human visual model, microinstrument, subpixel accuracy

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ТЕХНОЛОГИЯ ИЗМЕРЕНИЯ ГЕОМЕТРИЧЕСКИХ ПАРАМЕТРОВ МИКРОИНСТРУМЕНТА НА ОСНОВЕ МОДЕЛИ ЗРЕНИЯ ЧЕЛОВЕКА

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Разработана и реализована схема оптического микроскопа, включающего специальную бителецентрическую оптическую систему для формирования диодной подставки и телецентрического объектива для захвата изображения. Применение указанной системы позволяет снизить влияние дифракционных эффектов на краях теневой картины и измерять с помощью оптического микроскопа основные параметры режущего микроинструмента – его вылет и диаметр. Разработан алгоритм, моделирующий два основных зрительных канала глаза человека и детектирующий быстрые пространственно-временные процессы и шумы. Алгоритм обеспечивает измерение контура режущей кромки инструмента с субпиксельной точностью (до 0,01 пикселя) и позволяет определять физические размеры режущего инструмента с погрешностью 0,5 мкм.

Ключевые слова: телецентрический объектив, модель зрения человека, микроинструмент, субпиксельная точность

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Introduction

Machines and machining centers with CNC (computer numerical control) are the staple of modern metal fabrication (mechanical processing). Such machines can manufacture high-quality products with a given precision. The quality of production depends on a number of factors; some of them are dealt with at the stage of product design. A control program is created, material and tools are selected. However, real tools do not always exactly correspond to the objects designed in the program. While modern systems allow to adjust the operation of the machine to the actual size of the tool, this means that the exact parameters of this tool have to be known.

There are many ways (both optical and mechanical) to estimate and measure the parameters of cutting edges of tools [1]. Presetters based on optical micrometers are the most modern. These devices allow to obtain the necessary data on the geometrical parameters of the cutting tool quickly and in high quality. The accuracy limit is 5 μm for every 100 mm for such devices. There are as yet no modern tools for quick measurements on this scale.

This study is aimed at creating a device with the accompanying software and hardware technology that would make it possible to quickly and accurately measure such parameters of end-cutting and boring microtools as the overhang and diameter of the cutter, drill, tap, etc., before installing them into machine spindles with an accuracy no worse than 1 μm.

The technology is intended for rapid precise non-contact measurement and adjustment of cutting microtools outside the machine in a manufacturing environment.

We have designed and fabricated a device for presetting tools outside the machine (presetter). It is a hardware and software system with an optical micrometer and linear encoders. Special software allows to receive signals from micrometric linear encoders and optical micrometers and calculates the parameters of the tool. The results of the program are displayed on the screen. Interaction with the operator is through the software user interface.

Selection of parameters and development of optical scheme

A distinctive feature of the technology developed is that it is modeled on the human retina and uses bitelecentric optics to form diode backlighting and a telecentric lens to capture images. These tools allow to reduce the effect of diffraction on the edges of the shadow pattern.

Development of the optical scheme is one of the most important stages. The consumer properties of the entire device directly depend on the quality of the scheme. An accurately calculated and constructed high-quality optical system is absolutely necessary no matter how perfect the electronic circuit is. Otherwise, the distorted data received from it after mathematical processing may introduce significant errors in measurement accuracy. This means that special approaches must be taken to developing this system, from the standpoints of both science and design.

To construct optical circuits for an instrumentation system, it is first of all necessary to analyze and use the data on the required range and accuracy of measurements, on methods for calculating and tuning the optical node, on techniques for increasing its resolution and minimizing all kinds of aberrations.

The presetter is based on an optical micrometer (Fig. 1) with a bitelecentric lens and a beam path providing a clear, diffraction-free shadow of the edge of the microtool on an enlarged scale. This shadow is analyzed using an algorithm that finds extreme projection points and uses mathematical interpolation (see the next section) to calculate the coordinates of the points and the values of the radius and height of the microtool (the object of measurement).

The alignment of the lens and the radiation source should be coordinated with high accuracy in the optical scheme of the microscope. The diameter of the bitelecentric lens and the backlight is 16 mm and allows to generate an accurate, nearly diffraction-free shadow in the image plane of the photodetector. The system is designed to work with fixed objects, and the measured cutting edge is strictly coaxial with the spindle of the system.

In case of a telecentric beam path, inaccurate focusing does not affect the scale division of the tool. Lenses with bitelecentric beam paths, free from distortion and characterized by constant linear magnification, seem to be best suited for our purposes [2].

The optical micrometer is the most important part of the developed system; it consists of three main elements, a CMOS (complementary metal-oxide-semiconductor) sensor, a bitelecentric lens and a telecentric illuminator. There are presently two competing companies that are leaders in production of telecentric lenses: Opto Engineering (Italy) and

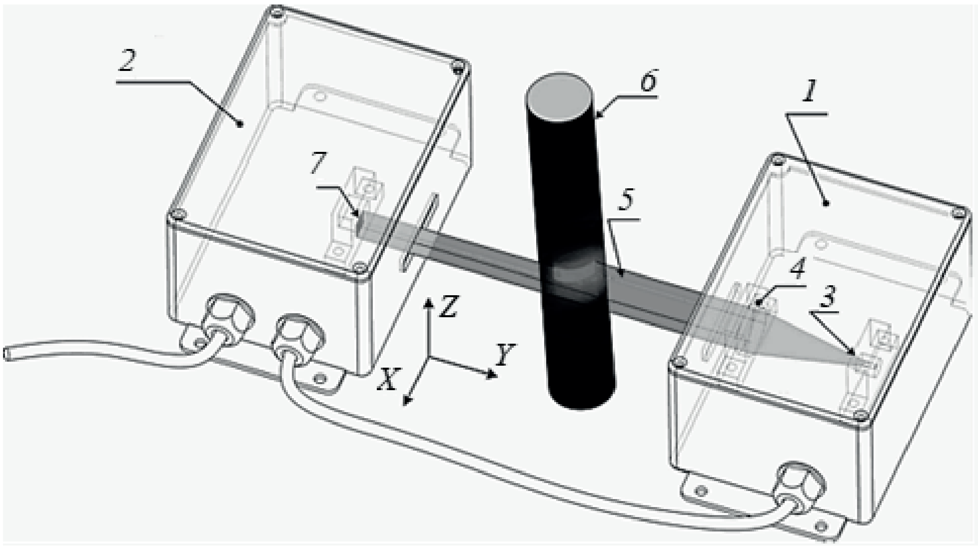

Fig. 1. Functional diagram of optical micrometer:
radiating unit *1*, receiving unit *2* , radiation source *3*, optical scheme *4*, scanning beam *5*, object of measurement *6*, photodetector *7*

SILL Optics (Germany).

The bitelecentric lens is selected in accordance with the requirements imposed on the parameters of the developed system (outlined below).

The bitelelectric lens only captures the beams parallel to its optical axis. Because of this, there is no perspective effect (when distant objects appear smaller than closer objects) and beams falling at an angle and reflected from other surfaces are not captured by the camera. However, the downside of this effect is that the lens only “sees” an area less than or equal to the area of the outer lens. The diameter of the outer lens is 16 mm. Thus, the lens allows to capture an area of approximately 200 mm^2.

The lens should be able to capture an area of at least 8 Ч 6 mm (based on the characteristics of the lens) so that the micrometer can be calibrated and effectively operate.

The second important parameter for finding the maximum focusing point is the depth of field of the lens. It should be no more than 2 mm for adjusting the cutting tool in the given system. This is the only point where the tool’s overhang can be measured correctly. Otherwise, the line on which the axis of the tool and its cutting edge lie will not be strictly perpendicular to the optical axis of the micrometer.

The third important parameter is the distance at which the measurement range begins. This distance can be calculated by subtracting the depth of field of the lens from its working distance (the distance at which maximum focus is achieved). This parameter must be taken into account in design of the optical micrometer.

Based on the above requirements, we chose TC 23009, a special bitelecentric lens by Opto Engineering (Italy).

A telecentric illuminator coordinated with the bitelecentric lens is necessary for the lens to operate correctly. The main requirement for the unit is that the diameter of the outer bitelecentric lens should coincide with the diameter of the outer lens of the telecentric illuminator. The LTCLHP023-R illuminator, also by Opto Engineering, fits this requirement.

To obtain correct images of the contours of the measured object, the components of the optical circuit should be arranged as follows:

The backlight module is located opposite the lens, and the axis of the backlight module coincides with the optical axis of the lens. The distance between the lens and the backlight module can range from 120 to 150 mm. We chose a distance of 125 mm (Fig. 2). The measured object should be located at a distance of 62.2 mm from the lens.

The CMOS sensor plays an important role in any optical circuit. As in the case of a three-dimensional triangulation meter with linear illumination, we used an industrial camera from Basler. In our case, there was no need for a high frame rate; the main requirement was that the camera should provide the image of the tool edge without “freezing”, i.e., frame delays on the screen were unacceptable. A camera with 25–30 frames per second proved to be sufficient for these purposes.

An industrial CMOS camera, Basler

acA2500-14um, was selected for this purpose. To give a complete picture, let us provide the characteristics of the camera:

Sony IMX264 sensor, 8.4 Ч 7.1 mm;

global shutter;

resolution (L Ч W) 2448 Ч 2048 pixels, pixel size 3.45 Ч 3.45 μm;

maximum frame rate 25 frame/s;

monochrome images;

C-mount;

USB 3.0.

Development and implementation of software interfaces and algorithms

The technology we propose includes a special image-processing algorithm. This algorithm is a spatial and temporal filter that simulates the two main visual channels of the human eye: foveal vision for detailed color vision and peripheral vision for detecting fast processes and events [3].

The retina consists of layers of interconnected cells. To build an algorithmic model of human vision, we selected two main layers of the retina: the outer plexiform and the inner plexiform. Each of the layers is simulated by special filters. The output of the algorithm is simulated by an inner plexiform layer.

Another important feature of the algorithm is that it can remove spatial and temporal noise while simultaneously enhancing image detail. Photoreceptors and perception of information by the brain are simulated in this case; the contrast of the image edges is increased, contours are improved, a logarithmic Gabor filter is implemented. The developed algorithm also makes it possible to increase the accuracy of detecting the contours of objects to subpixels.

Fig. 3 shows images illustrating the changes in sharpness of the object's contour. For example, blurring at the edges of the object is greatly reduced. The differences in intensity are also practically absent in the elements of the object.

We developed a data exchange algorithm making it possible for the optical micrometer to interact with a personal computer. At the physical level, the interaction happens via the USB 3.0 interface. A set of functions is implemented to build the logical level, allowing to connect and control different parameters of the optical micrometer. These parameters include exposure time, gain, range of interest, frame rate. To get real-time images, we used the functionality of the Pylon and OpenCV libraries. The functions for receiving frames and transmitting them for further processing are performed, in accordance with our projects, in separate streams, which allows to achieve high speed at a frame rate of 25 frame/s.

The algorithm also contains functions for detecting (with subpixel accuracy) the contours of the cutting edge of the tool in an image obtained with an optical micrometer.

This image has certain specifics because of telecentric optics used:

diffraction effects at the edges of the tool are minimal;

dimensions of the object image on the matrix of the video camera match the real dimensions of the object.

Thus, knowing the physical size of the pixel on the video camera matrix and the number of pixels occupied by the contour, we can calculate the position of the tool's edges (in micrometers) relative to the optical axis of the camera. With this approach, the positions of the tool's edges can be detected with pixel accuracy. The matrices used in most modern video cameras have a pixel size that

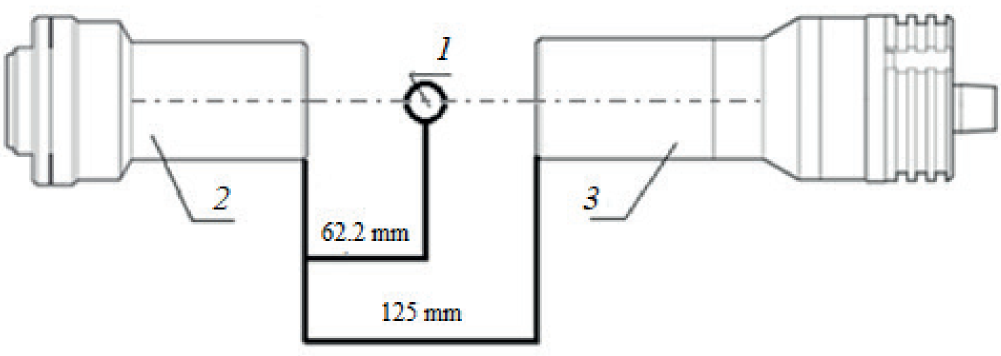

Fig. 2. Layout of components in optical system:
measurement object *1*, bitelecentric lens *2*, backlight module *3*

does not exceed 3–4 μm. This parameter value does not guarantee that the required dimensions are detected with micrometer accuracy.

To detect the edges of the tool more accurately, we have developed an algorithm with subpixel accuracy and used its functionality.

There are three main groups of methods for detecting the contours with sub-pixel accuracy:

approximation methods;

methods based on calculating the image moments;

interpolation methods.

The methods of the first group use continuous functions to fit the image function. The subpixel position of the contour is defined as the inflection point of a continuous function.

The methods of the second group use statistical models.

The methods of the third group provide subpixel accuracy by interpolating image data to obtain a finer grid of pixels [4].

The algorithm that we developed belongs to interpolation methods (third group).

The algorithm consists of the following operations.

Step 1. Gaussian blur is applied to the image.

Step 2. A filter with a Canny kernel is applied separately for rows and columns; results are recorded in the corresponding matrices.

Step 3. The points of the contour are detected with pixel precision.

Step 4. The position of the contours is refined with subpixel accuracy based on the contours obtained in Step *3* and the matrices recorded in Step *2*.

The subpixel coordinates of the contours are calculated by setting the position of each of the points of the contour in its 3 × 3 neighborhood. Eigenvectors and eigenvalues of the Hessian matrix of a given neighborhood are found next [5]. Because of this, the direction and magnitude of the contour point offset are found relative to the initial ones. Thus, when each point of the contour is shifted by a certain vector, a subpixel value is found for the position of each point of the contour.

The method developed makes it possible to obtain the sought-for values with an accuracy of 0.01 pixels. Such accuracy allows to determine the physical dimensions of the measured tool with an accuracy not less than 0.5 μm.

Geometric parameters, such as overhang and diameter, are calculated as follows. Subpixel coordinates of the contour points are analyzed, with the minimum and maximum points searched by x and y coordinates. The point with the minimum value of the x coordinate corresponds to the tool point most distant from the axis, and the point with the minimum y coordinate to the tool point with the maximum height. The values of the characteristic points are then converted to world coordinates by multiplying the coordinate value by the pixel size in the corresponding direction and by the magnification factor.

Precise image focusing is necessary to obtain the most accurate images. A function calculating the value of the Laplacian of the image (it represents the summed value of second-order derivatives) is used to control focusing. Next, the standard deviation for the Laplacian matrix, i.e., the "focusing" value of the image, is calculated. The degree of focusing of the image is estimated by the value of the parameter obtained. This algorithm includes a threshold value of the parameter, separating the "focusing" values into acceptable (that can be used for measurements) and unacceptable (focusing should be improved if these values are reached) [6].

In addition to the above, we implemented a system for calibration by a given template. The software was developed in the Qt Creator environment using the Qt and OpenCV libraries.

The OpenCV 3.1.0 library intended for image processing was used to develop the functional module of the program. The image received from the camera contains information about the con-

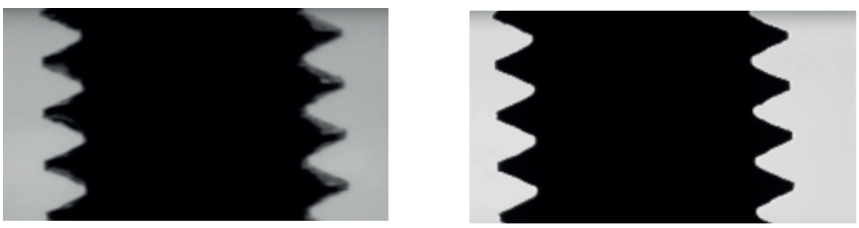

Fig. 3. Comparison of two images of object:
source *a*, processed by algorithm for removing spatial and temporal noise *b*

tours of the object. This image is generated by a telecentric optical scheme allowing to capture images with virtually no diffraction around the edges of the object. This simplifies the task of detecting the contour of an object for further measurement.

In order to increase contrast, we applied an algorithm based on a model of human vision. The object's contours were then detected with subpixel precision. For example, if lens magnification is 1.005, an estimate for the size of the contour on the matrix of the video camera can be made. This size is equal to the number of pixels that the contour occupies, multiplied by the pixel size and magnification factor.

For example, to calculate the size of the contour along the horizontal axis X

$$X = dNp,$$

where d is the lens magnification factor, N is the number of pixels between the edges of the contour, p, μm, is the pixel width.

To calibrate contour size, a template object with known parameters is measured. The position of the rotation axis of the tool in the coordinate system of the camera matrix can be then determined. For example, a cone can be used as a template.

The calibration module allows to determine the position of the point with the maximum value of the Z coordinate (it corresponds to the axis of rotation).The value of the X coordinate corresponding to the axis of rotation is taken to be zero for calibration. In other words, the vertex of the cone serves as the origin of coordinates in the XZ system. The initial value of the Z coordinate is defined as the difference between the obtained value of cone height subtracting the actual cone height (Fig. 4, *a*).

The user interface developed for the measurement mode (Fig. 4, *b*) contains the following areas: image view from the optical micrometer; input of measurement results.

Conclusion

We have carried out a study aimed at creating a device and the accompanying software and hardware technology for quickly and accurately measuring the main parameters of cutting tools. We have obtained the following results.

1. We have developed an optical microscope and an optical scheme for it, including bitelecentric optics for diode illumination and a telecentric lens for image capturing. The lens of the optical microscope has a depth of field less than 1 mm (images are generated without diffraction).

We have established that such an optical scheme allows to reduce the effect of diffraction at the edges of the shadow pattern and measure such parameters of the cutting tool as the overhang and diameter with an optical microscope.

2. We have developed an algorithm detecting fast spatial and temporal processes; it provides measurement of the cutting edge contour of the tool with subpixel accuracy (up to 0.01 pixel) and the physical dimensions of the cutting tool with an accuracy up to 0.5 μm.

a) *b*)

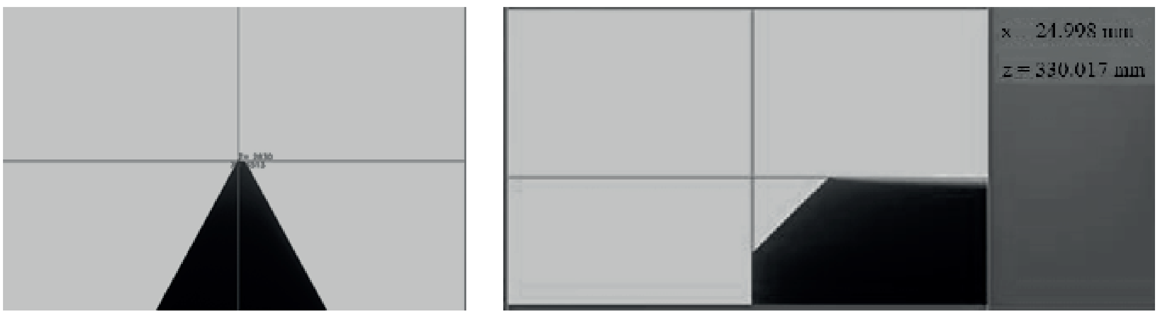

Fig. 4. Example of user interfaces
for calibration (*a*) and measurement (*b*) of size of cutting edge contour;
A cone was used as a template.

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