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Intelligent systems for monitoring and controlling chip formation when cutting difficult-to-machine materials

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Abstract. This research addresses topical issues of creating industrial monitoring systems for chips, which are formed when materials are cut, based on light field-based optical detectors. A proposed scheme uses a light field (LF) method to register formed chips with an optical detector. An algorithms and monitoring methods for key geometric parameters of chip shapes are developed based on the analysis of images obtained from LF cameras. They feature digital image capturing and morphological analysis. For practical implementation of developed algorithms, National Instruments software platform is used. This research shows that the result accuracy in determining geometric characteristics of chips using the proposed solutions makes it possible to run diagnostics for cutting and material processing equipment.

1. Introduction

When materials are processed by cutting, geometric structure parameters of formed chips depend on the state of the equipment and used cutting modes. However, chips are not only the source of technological information about cutting modes. They are secondary raw materials, which makes it an important issue to package them in an optimal way for transportation and further processing. To achieve it, special methods are developed for chip fragmentation during the technological process. Studies on chip geometric parameters yield important information about technological conditions and the state of equipment necessary for each type of processed materials. Thus, ensuring specified chip parameters is important to establish the technological process. At the same time, parameters of the formed chips can be used to control the technological process of cutting. In real life however, it is extremely hard to objectively monitor geometrical parameters of the formed chips and their surface state.

Optical methods based on image recording of monitored objects can be efficiently used for control purposes in manufacturing as they provide an opportunity to build automated control and monitoring systems. However, it is difficult to use them to control complex three-dimensional objects, thus preventing full implementation of high-performance monitoring systems for large-scale objects. Construction of such systems ensures that technological equipment operates in a closed-loop mode and allows for unmanned, highly automated digital production. Therefore, development of intelligent systems for monitoring and controlling chip formation when difficult-to-machine materials are cut during unmanned production, as well as optical systems for image recording for three-dimensional objects is a pressing challenge.
2. Materials and methods

Chips formed by material cutting are three-dimensional objects of a complex spatial structure that cannot be defined in advance. A number of its geometrical parameters corresponds to a processed material type, equipment and technological modes used for cutting (Figure 1). These parameters are as follows: thickness, width, diameter and turn spacing. Chip surface defects and microrelief are also important parameters.

![Figure 1. Chip samples: 1 – steel, grade 45, 2 – D16T aluminum alloy, 3 – 08X18H10T stainless steel (AISI 321 analogue).](image)

The analysis shows that non-contact methods, including optical ones, are preferable for determining chip shape parameters and defects. It is known that unlike system-focused optical imaging methods, light field (LF) imaging allows for luminance registration not only by coordinates, but also across directions of emanating from all surface points [1]. This makes it possible to record flat image layers with a large depth of field and change the camera's viewing angle relative to the object of control via software [2]. This is achieved by introducing an additional microlens array in front of a digital camera's photodiode matrix [1]. An optical system of the LF camera (OS – Ω) is represented by the main projecting lens (L) and a microlens array (MLA) located in front of the photodiode matrix. A principle of light field file (4D) generation in the LF OS can be described via matrix optics [3].

A flat image (2D) of the surface brightness structure is formed using an algorithm that sums signals from photodiodes of the receiver under the microlenses. It establishes a set of $L_i$ rays that compose an image of the remote surface from the OS of the LF camera ($z$) in a certain layer of space ($Δz$):

$$\text{Im}(z, Δz) = \bigcup_{z \in D_v} L_i(x, y, \varphi),$$

where $z$ is the distance from surface points to the OS, $D_v$ is a virtual aperture of the OS.

It allows for controlling not only geometric parameters of produced complex-shaped items, but also shape characteristics and surface defects via a morphological analysis of different image layers [4, 11-13]. All necessary information can be obtained via a single LF camera and a single frame exposure. Currently, there exist industrial prototypes of LF cameras (Lytro, Retrix) [5] that are successfully used in manufacturing to control three-dimensional objects.

Popular methods of digital image processing can be used to process and measure geometric parameters in the image structure. The use of modern computer technologies, for example, National Instruments (NI) products [6], enables automation of the measurement in the technological process [7, 14-16]. However, full-scale industrial automation is only possible if digital cameras used are supported by the NI IMAQ-Vision driver. Therefore, it is not always possible to implement data collection and processing via one software system [17].

In this regard, it is necessary to analyze chips fragment images received via the LF camera, develop algorithms of chip processing and parameter measuring in order to determine required parameters.
Due to the fact that LP cameras that currently exist are not equipped with automated imaging and real-time processing, this problem has not been addressed yet. These solutions will allow for improving the quality and reducing the cost of production through live monitoring of the technological process.

The aim of this research is to find out if LF cameras can be used to determine shape geometric parameters and qualitative parameters of chips formed during cutting. In its turn, it will allow for controlling parameters of the technological process and the state of the cutting equipment.

3. Experimental studies

In this study, chips after metalworking operations are used as samples. The structural and functional scheme of the experimental setup for controlling chip parameters is shown in Figure 2. Chip imaging was obtained using a setup with several digital cameras (DC).

![Figure 2. Structural and functional scheme of the experimental setup for chip monitoring.](image)

The chip sample I is placed on the rotary table 2, which is rotated by a step motor 3 (FL39ST38-0504A) via a programmable controller 4 (SMSD-1.5) and a circuit board to form logic signals (USB 6009). Blocks 4 and 5 are powered by source 6 (S-350-12). The sample is illuminated by a light source 7, with the illumination level controlled by a luxmeter 8 (DT-61). For this setup two light field cameras are used: 9 and 10 (Lytro ILLUM). They can be located either parallel to each other (I) or radially relative to the sample (II). In the first case, light field cameras work as a single LF detector, which allows for increasing of the virtual aperture via the software (i.e. reducing the depth of field – increasing the number of recorded image layers). The radial arrangement of the cameras (II) is equivalent to a stereo shooting mode. However, a greater depth of field in each direction can be recorded. A stereo pair of flat images, if necessary, allows for a 3D reconstruction of the monitored sample [8] with subsequent synthesis of different angles. The computer 11 via a data acquisition board 5 programmatically sets rotation of the table 2. Table 2 rotation is controlled by a virtual device 12 (VD 1). A virtual device 13 (VD 2) is used for image processing to establish parameters of the sample. Figure 3 displays optical registration part of the experimental setup.
Figure 3. Part of the setup for registering chips by two light field cameras.

Flat images of chips used for measuring geometric shapes are created in the application LytroDesktop from a LF file (4D) with the maximum depth of field. The easiest way to obtain geometric parameters for non-intertwined (twisted) chips is to outline chip edges and construct functional dependencies $y_i = f_i(x_i)$, the analysis of which allows for determining their basic geometric parameters. For digital capturing of weakly localized structures in the image, an algorithm and an application developed in Ni LabVIEW framework were previously proposed [9]. The algorithm of this application uses a profile line scanning method into an image with subsequent detection of luminance distribution. The latter is achieved by finding the exact luminance contrast coordinates at the maximum coefficients of the continuous wavelet transformation (CWT). Analysis of the CWT coefficients curves, given the controlled luminance value and exposition, make it possible to estimate chip surface topography, thickness and width.

A workspace of a virtual device (VD), i.e. a digital image capturing application [9] created in Ni LabVIEW framework, is shown in Figure 4. For image digitization, sample 1 was used (Figure 1). A filtering algorithm (IMAQ Convolute) outlines curves of contrast gradient contours that correspond to the outer edge of chips (panel 1). Contouring functions are configured by detecting coordinates of the maximum values of the external and external contrast curves in the profile lines (panel 2). The latter can be used to construct a 3D shape of the chip surface, given the image perspective (the viewing angle of a digital camera). A diameter and width of the chip can be determined based on the digitized contour image, as well as external (A, B) and surface (C) defects based chip shape contour lines.

Figure 4. A workspace of the digital image capturing application for chips.
Different measurement algorithms from a Ni IMAQ Vision machine vision software module can be used at the same time to determine the geometric parameters of the chip. For example, the following can be used: Find Straight Edge for finding straight lines on the outline edge at the top and bottom, Caliper to measure the distance between the identified lines, Find Circular Edge to find the external and outer radius of the equivalent circle or curve, Contour Analysis to analyze the contour shape.

For complex-shaped chips, it is quite difficult to perform analysis of chip parameters based on the digital image. For this purpose, a morphological analysis for the whole image can rather be used. The proposed approach is as follows: binary clusters are formed for the image between continuous edges of the chip shape contrast gradient outlines. Next, the cluster shape analysis is used to remove certain fragments from the image. This problem was solved using a set of out-of-the-box functions (data processing nodes) of the IMAQ-Vision module [5, 10]. One of the algorithms of using these functions is shown in Figure 5. Function description and set parameters for the image (Figure 6) are shown in Table 1.

![Figure 5. The algorithm (script) processing of a complex-shaped chip image.](image)

All algorithm functions for obtaining the required analysis results support parameter setting for functions (data processing nodes). Algorithm parameters were interactively set up in NI Vision Assistant 2013 [11].

| No. | Function Icon | Function Name        | Description and Parameter Values                                                                 |
|-----|---------------|----------------------|---------------------------------------------------------------------------------------------------|
| 1   |               | Original Image       | Captures image: specifies file name and location.                                                  |
| 2   |               | Color Plane Extraction | Extracts colored planes from an image (RGB, HSV or HSL). Set value: RGB-Green Plane.             |
| 3   |               | Threshold            | Selects a range of pixel values in the grayscale image.                                            |
| 4   |               | Advanced Morphology  | Performs high-level operations on binary image clusters. Removes small objects.                  |
| 5   |               | Basic Morphology     | Changes the shape of binary objects in the image. Fills holes in particles.                       |
| 6   |               | Binary Inversion     | Changes the display dynamics of an image that contains two shades of gray.                       |
| 7   |               | Circle Detection     | Finds the center and radius of circular particles in the image.                                  |
| 8   |               | Conversion           | Converts the resulting image to a specified image format.                                         |
The choice of some parameters values is determined by the image quality (for example, parameters of obtaining a flat image from the LF file), lighting conditions, positioning of the DC. The result of the algorithm is shown in Fig. 6.

![Figure 6. The result of the chip size measurement and processing algorithm.](image)

The resulting binary image contains a continuous cluster between the chip shape edges obtained from the luminance structure on the optical detector. As a main measuring function, the search for circles that fit in a cluster (Circle Detection) of a given radius ($R_{\max} - R_{\min}$) was used. The distribution of circle coordinates along the chip contour determines parameters of its contour shape, while the distribution of circles by radii along the contour determines the statistics of chip width.

To highlight an image with parameters of the relief shape and surface defects, the correlation of several image layers located at different $z$ distances along the space depth $\Delta z$ (along the Z axis) is used. The correlation of layers based on selected morphological functions ($M$) determines a geometric structure and local defects (quality) of the surface by chip surface array depth [4]:

\[
\therefore \left( \text{Im}_1, \text{Im}_2 \right) = R_1 \text{Im}_1(\varepsilon_1, \Delta z_1) \otimes R_2 \text{Im}_2(\varepsilon_2, \Delta z_2),
\]

where $\therefore$ is a correlation type of image layers, $R$ is additional transformation of the image layer (histogram, shift, scale, rotation).

The created algorithms for chip geometry and surface analysis based on flat images can be used to create an automated monitoring system for chip parameters (shape and size) in the technological process. Studies have shown that algorithms presented in this research are robust by random chip formation and can be used to objectively assess the chip formation process.

4. Conclusion
This research has shown the possibility of high-precision control over the geometric parameters of the chip shape, micro- and macro-surface topography and distinctive defects in 3D by one LF digital camera with a single exposure. It allows for on-the-spot usage of the proposed method to control results of cutting process in industrial conditions. High-precision algorithms for digital capturing of simple twisted chips can be used to simplify and obtain direct quantitative estimates of the main chip
geometric characteristics. Analysis of binary clusters in a form of simple and complex-shaped chips allows for gathering objective qualitative statistics data on chip width. They can be used as objective parameters of chips in the technological process of cutting materials, the state of the cutting equipment. Developed hardware and software approaches can be used to automate the chip monitoring process in industrial manufacturing.

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