Shape and Relief Evaluation Using the Light Field Camera

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Abstract. The paper considers an optical system for controlling the shape and micro-relief of products using a single-camera optoelectronic light field recorder. Based on National Instruments computer technologies, image processing algorithms and basic surface measurements have been developed. To accurately determine macro- and micro-relief parameters the authors propose algorithms for morphological analysis of two images obtained from a multi-focus light field file at a given depth of field. It is shown that the method of capturing the light field makes it possible to obtain the accuracy of surface relief by the height of its profile compared to other methods, while significantly reducing control requirements.

1. Introduction
Optical instruments are widely used in industry to control the shape, deformation and roughness of a surface. Optical methods are high-performance contactless means to control manufactured products. Stereo systems enabling to acquire images of the same scene from different points of view with two or more cameras are used to control 3-D scenes. Mathematical analysis called triangulation is applied to determine the shape of a surface. Stereo triangulation is based on the search and identification of identical points representing images (the object should have a pronounced structure). In this case, it is necessary that the optical recording system has a sufficient depth of field.

Depth from focus methods (DFF) are techniques for determining the relief by the focus based on distance estimation by several images obtained from different points of view to the focusing optical system.

Optical recorders have recently become available to capture information about the intensity and the direction of rays from the scenes referred to as the light field cameras (LFC) which enables to capture an image equivalent to 200 plane layers of space with one camera in a single exposure. Given the right algorithm for forming a 2D image from a light field file makes it possible to partially change the direction of LFC live view and filter some of the rays while they are travelling in space. This opens up new possibilities for controlling the surface of 3D objects. So far, it has been studied how to obtain LFC images as well as methods and possibilities to reveal 3D surface features. However, the metrological issues of this type of control have not been considered yet. The practical way to control the shape and micro-relief based on metrological requirements creates a basis for a wider use of this type of control in industry.

It should be noted that shape and micro-relief control based on metrological requirements still remains a topical issue.
2. **Purpose of research**

The paper aims to investigate the system for measuring geometric parameters of the relief and shape of various objects by their images obtained from the light field camera, to compare the results of control with the measurements obtained on the certified standard finished samples and to determine the method of monitoring and evaluation of geometric measurements of the surface shape.

3. **Materials and methods**

Since the method of recording the light field (LF) enables to capture the coordinates and direction of the rays emanating from the points of the object’s surface [1], there are prerequisites to control not only the geometrical parameters of objects with complex shapes, but the surface relief features as well [2]. The problems concerning 3D image formation are considered in detail in the papers [3] and [4].

Image layers are energy wavefront samples carrying information about the scene. Morphological image operations are a measure of wavefront correlation. This enables to obtain comparative information along the registration direction for different points of the surface, i.e., to obtain parameter that determines the character of the relief of the surface $z(x,y) - S(x, y, z)$, as a measure of contrast of points on the image layers $\text{Im}_{3D}(x,y,z)$:

$$\Omega_{xy}^\Theta = \{(x_i, y_i)\}^\Theta \subset \Xi^G(I)\{\text{Im}_{2D}^\omega(x, y) \subset \text{Im}_{3D}(x, y, z)\},$$

where $\Xi^G(I)\{}$ is the retrieval and evaluation algorithm for the points $(x_i, y_i)$ for a specified image focusing, $\Theta$ – specified regions of illumination histogram for selecting points determined by the optical properties of the surface.

It is always difficult to control 3D surfaces that have homogeneous optical properties or demonstrate optical transparency [5]. Therefore, polymer-based articles obtained by 3D printing [6] were used as the main objects to study the shape and relief of the surface. In addition to technological printing heterogeneities, an additional regular convex or concave surface height structure (QR-barcode structure) was created to conduct surface research. The surface image of this type of products was recorded by the Lytro ILLUM light-field camera [1, 2]. The simulation model for recording the mirror body for the Jamin interferometer is shown in Fig. 1. The upper surface image $I$ was illuminated by oblique light rays from the ring illuminator $2$. The surface was recorded by the light-field camera with the main lens $3$, the system unit with the display $4$.

**Figure 1.** Simulation LFC model:

1 – Polymer-based article with 3D barcode on the surface; 2 – Ring illuminator; 3 – LFC lens; 4 – LFC system unit with display
The obtained LF file further resulted in plane images [6] formed in LytroDesktop with a given focus setting near the surface and the selected depth of field which corresponded to the set of rays forming these images. The image processing and necessary measurements were performed in National Instruments (NI) - NI LabVIEW environment with NI IMAQ-Vision driver functions [7].

To determine the shape and relief parameters by the surface depth, the correlation functions for the layers located at different distances \( z \) along the depth \( \Delta z \) of the field (Z axis) were used. This approach compared the rate of change in the luminance gradient of layers in the image plane. The correlation functions of two plane layers \((\ldots \otimes \ldots)\) were realized by binary functions of the morphological analysis \((M)\) of selected image layers:

\[
\text{Im}(z_1 : z_2) = \text{Im}(z_1, \Delta z_1) \otimes M(\text{Im}(z_2, \Delta z_2)),
\]

where \( \text{Im}(z_1, \Delta z_1) \) and \( \text{Im}(z_2, \Delta z_2) \) are two image layers with the focus setting \( z_1 \) and \( z_2 \), depth of field \( \Delta z_1 \) and \( \Delta z_2 \) respectively.

The morphological function \((\ldots \otimes \ldots)\), represented in the NI IMAQ-Vision module by the Color Operation function which allows the following binary operations \((M)\) with two image layers [8]: Add, Subtract, Multiply, Divide, Multiply Divide, Modulo, Absolute Difference, And, Not AND, Or, Not Or, Exclusive Or, Not Exclusive Or and Logical Difference.

As shown earlier [8], the morphological operation Modulo applied to the two selected layers of the light field image better evaluates the micro features of the surface, and the Not AND operation - the macro features of the surface. The height of the relief and the deviation from the plane are determined by the relief function \( \Delta z(x, y) = f(z_1, \Delta z_1, z_2, \Delta z_2) \). The shape of the surface was determined by the relief curves of the selected heights \( f(x, y, z) = \text{const}(\Delta z) \).

4. Results and Discussion

LF recorder enables to obtain an image that contains fragments of 3D surface in the information field. The LF information capabilities are determined both by the height of surface sections and the interaction of light rays emanating from the illuminator with the surface (the indicatrix of scattering of light rays by the surface points) [1]. The shape and relief of the object’s surface under study can be described as follows:

\[
S(x, y, z) = R_0 \{S_0(x, y, h_0) + S_1(x, y, h_0 + \Delta h) + S_2(x, y, h_0 + z)\} + S_3(x, y, z),
\]

where \( R_0 \{\ldots\} \) are surface transformation functions in the process of LFR editing (rotate, curvature), \( S_0(x, y, h_0) \) is the basic structurally defined surface of the object, \( S_1(x, y, h_0 + \Delta h) \) is the given information structure of the surface, \( S_2(x, y, h_0 + z) \) is the technological structure of the surface.

Therefore, to ensure a thorough surface analysis by the method of morphological operations of image layers, it is necessary to use image transformation functions [9], for example, changes in their color characteristics and geometry [10]:

\[
\text{Im}_e(z_1 : z_2) = R_1[\text{Im}(z_1, \Delta z_1)] \otimes M(\text{Im}(z_2, \Delta z_2)),
\]

where transformation operators \( R_1 \) and \( R_2 \) specify the given rotation, scaling and displacement in image layers (in this case \( R_1 = R_2 \)).

The algorithm for processing two layers of LF file, developed in NI Vision Assistant is shown in Fig. 2.

![Figure 2. Algorithm for processing two image layers](attachment://image.png)
The first image I is saved in the image buffer 3, after that the second image 4 is loaded. Functions 2 and 5 (Geometry) enable to rotate and scale the images to provide additional calibration of the layers. Each image can be processed by applying some additional series of image processing functions: $F_{\Sigma}^{(1)}$, $F_{\Sigma}^{(2)}$. The presented algorithm enables to analyze one image in the form of its two copies obtained by changing their geometry and other parameters thus implementing a more complex 3D correlation analysis of rays forming the light field. The applied binary operations 6 with two images $(z_1, z_2, \Delta z)$ result in the image shown in Fig. 3a, 3b.

In the first case (Fig. 3b), the intensity of illumination in the resulting image reveals surface characteristics against the main surface. In the second case (Fig. 3c), the elements of height information can sufficiently be identified on the surface (QR-barcode). The identification of the required information during morphological operations is affected by the nature and uniformity of surface illumination along with some other factors. Hence, morphological functions with image layers enable to obtain a new two-dimensional information structure, whose analysis accounts for the desired surface parameters (microrelief and macrorelief), and the conditions for obtaining the light field, e.g., the performance of a parametric illuminator.

![Figure 3. Plane surface image and result of morphological operation:](image)

*Figure 3. Plane surface image and result of morphological operation:*

*a) Converted plane image from LF file; b) Result of Modulo operation*

*c) Result of Not AND operation*

Metrological studies of shape and microrelief measurements were carried out on the standard finished samples SFS-T No. 2346: Ra12.5, Ra6.3, Ra3.2, Ra1.6, Ra0.8, Ra0.4 (Fig. 4a).

![Figure 4. Set of standard finished samples (a), 2D standard finished sample (b)](image)

*Figure 4. Set of standard finished samples (a), 2D standard finished sample (b)*

The LF file was transformed to plane images corresponding to the layers of a given depth of field near the surface (Fig. 4b). The figure shows the brightness structure which determines the geometric character of the roughness, and luminance gradient proves the deep nature of the relief. However, direct analysis of the luminance gradient doesn’t provide an accurate geometric depth measurement.

To estimate the plane shape and relief image, a step-by-step 2D processing algorithm is used to give the surface geometry parameters by its brightness segmentation (Watershed Segmentation) that determines the structure of the surface microrelief (Fig.5). The figure shows that the segmentation
function adequately reflects the roughness step. Nevertheless, it does not give results as to what the shape of the relief is (the size of the cylindrical surface and the depth of the groove). Such a result can be ensured by the morphological analysis of image layers. Due to the cylindrical nature of the sample, the result is obtained only in a certain section of the surface. The wider the layers, the wider the section, but the accuracy of geometric height measurements decreases.

Thus, different functions of the algorithm make it possible to evaluate various parameters of the surface. The accuracy of evaluation is compared to the accuracy that can be achieved by other methods and means of control. However, the method of LF recording makes it possible to implement a retrospective analysis of earlier data resulting in the evaluation of the desired shape characteristics.

Experimental studies have shown the capabilities provided by LFC to determine the geometry of the shape and relief of the surface. Unlike other contact and non-contact methods, LF recorders have a wider range of surface measurements and do not require pre-focusing. The shortcomings of LFCs are a considerable time required for processing LF files. Currently, there are no available manufactured LF recorders. There are difficulties related to the real-time control taken in the unified data recording and processing software. However, existing LF recorders demonstrate the ability to control the shape of products and achieve metrological specifications in line with standards.

5. Conclusion

The paper shows that the method of LF recording makes it possible to evaluate the geometric parameters of microrelief and shape of the surface by the plane and depth. The accuracy of measurements increases with the size of the surface. The results obtained on the certified standard finished samples establish the relationship between the measurement results from the light field camera and the real geometric parameters of the surface shape of the samples.

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