Study of possibilities for light marker coordinate measuring with light field digital cameras

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Abstract. The paper considers the possibilities of recording the laser emitter light markers on the surface of the object under study by an optoelectronic system based on digital light field cameras. The technique of experimental research of coordinates and parameters of light markers is described. The mathematical model of light markers is presented. Algorithms have been developed for determining the coordinates of light markers on the surface of controlled products. The accuracy of determining the coordinates and dimensions of light markers is analyzed. The necessity for high-precision measuring systems to perform preliminary calibration of laser emitters according to the proposed method, taking into account the design range of light markers, is shown. It was found that the accuracy of determining the coordinates of light markers for design surfaces with digital cameras of the light field is several times higher than with conventional digital cameras.

1. Introduction

Nowadays, the issues of determining the coordinates of small-sized light objects are relevant. Small-sized objects include light remote objects or light markers (LM) designed by laser emitters or modules. Laser models are widely used in measuring systems employed in various fields of technology, where the information parameter is determined by the LM coordinates on the projected surface. Such areas include photogrammetry [1], target acquisition and destination systems, navigation, etc.

Today, laser emitters, including semiconductor laser modules with low emission divergence, have become widespread. Emissions of many of them have a large scattering of parameters and considerable variations in the brightness pattern at different design emission distances, which is associated with the forming peculiarities of laser emission [2].

Measuring the true or relative coordinates, size, and other characteristics of the LM on the projected surface is always associated with a number of difficulties. First of all, with the optical properties of the surface and the properties of the optical system for designing the LM on the photodetector of the recorder, which affects the accuracy of determining the coordinates of light markers on the projected surface. The choice of an optical-electronic LM registration system, an algorithm for processing images of light markers, and an algorithm for measuring their parameters remain important issues. Currently, these issues are solved in particular tasks, under given fixed conditions. The main difficulties are the high and highly localized brightness structure of the LM, which is unstable from a distance. There is no method for calibration of the measuring system in a wide range of uncontrolled conditions.
The task of high-precision determination of LM coordinates in a wide range of their design distances and different laser emitters is very relevant, as it will increase the accuracy of orientation systems and expand their scope of application.

2. Method Overview
Emission parameters of laser emitters are determined by its characteristics and the optical forming system of emission [2]. Emission pattern of the laser emitter is determined by its design. At the same time, the accuracy of sighting of the optoelectronic system (OES) by the laser emitter markers is defined by the ability to determine the coordinates of the light spot on the surface of the object by means of an additional optical system, which is determined by the optical magnification, type and resolution of the photodetector. When choosing laser emitters, it is necessary to take into account not only static, but also dynamic characteristics of the LM [4].

Matrix photodetectors based on CCD and CMOS type photodiode matrices are today widely used for registering the brightness structure distribution [3], which in most cases makes it possible to automate the input of the registered brightness structure into a computer system and carry out its subsequent processing [4]. Currently, hybrid OES are being developed that allow registering the coordinates and directions of the rays included in the OES [5] - light field recorders (LF), which are an array of low-resolution digital cameras. This solution allows you to expand the dynamic brightness range, eliminate the mutual influence of photodiodes, and conduct angular filtration of incoming rays. Previously, it was shown that digital cameras of the light field, according to a number of criteria, are capable of providing a higher image quality [6], have less spatial distortions.

For automated input of brightness fields from various recorders, national Instruments (NI) technologies are used, which include the Ni LabVIEW graphical programming environment [7], tools for developing adaptive algorithms (NI Vision Assistant) and building industrial continuous monitoring tools (NI Vision Builder for Automated Inspection) [8]. Together with NI LabVIEW, mathematical methods for signal processing based on combined time-frequency (JTFA) and wavelet analysis (WA) [9], which are implemented in the additional Ni Advanced Signal Proceedings Toolset module, are used. These methods expand the possibilities of image processing and make it possible to increase the accuracy of measuring weakly localized brightness structures in conditions of noise and mechanical instability of the control system. Thus, to conduct research on the accuracy of determining the parameters of laser emitters, it is advisable to use technologies and solutions from National Instruments, which allow one to create and test prototypes of industrial and embedded systems, carry out their modernization and scaling.

In view of the comparative novelty of the technology of LF recorders and the complexity of their communication with computer systems, studies of the accuracy of determining the coordinates of brightness structures obtained on the surface by laser emitters with digital cameras of the light field have not been conducted before. Conducting these studies will enable the development of LF recorder technology and scope of application.

3. Technical Tools for Research
The digital camera (DC) Lytro ILLUM (version B5-0036 ILLUM) [10] with a CMOS sensor (Aptina MT9F002 14.4 Mpix, 1/2.3 ”, effective image area: 6.14 × 4.6 mm, pixel size 1.4 μm) was used as the LF recorder. The number of microlenses in the array is 130,000 (focal length 25 μm, pitch 13.89 μm). The recorder had a built-in lens of 9.5-77.8 mm with a relative aperture of f/D = 1:2. The maximum resolution of the DC in the image it receives: 2450x1634 Pixels.

As an alternative comparison recorder, the Canon EOS M high-speed resolution DC was used, which had an APS-C matrix (22.3 x 14.9 mm, a CMOS matrix of 18.5 million pixels, a maximum resolution of 5184 x 3456 pixels, pixel size of 4.3 μm²). Lens CANON ZOOM LENS 18-55 1: 3.5-5.6.

For processing LF files, the original Lytro Desktop application, the NI LabVIEW programming environment, and the NI IMAQ Vision driver were used.
4. Theoretical research
The basis of measuring systems is to determine the relative position of several LMs. In order to analyze the accuracy of measuring brightness structures, a model of the relative position of light markers was developed, implemented in a virtual instrument (VI), the front panel of which is shown in Figure 1.

Figure 1. Model of relative position of light markers
VI sliders 1 and 2 set contour coordinates of left (X1) and right (X2) markers, 3 and 4 - set width of left and right borders of brightness transitions of LM (b1, b2), 5 - set relative illumination levels LM A2/A1. Control 6 selects the type of functions of LM contour and the shape of unevenness of light zone. The type of the selected functions is displayed on the graphic indicator 7. The additional control group 8 defines edge effects in the shadow zone (amplitude, length, oscillation frequency). Group of controls 9 "Vibrator" allows to mathematically transform the given contour into the mode of the specified mechanical instability (blur). The distance between two shifted light markers is set by control 10, indicator 11 is displayed. The control 12 specifies the amplitude ratio of the illuminations in the light markers. Graphic indicator 13 displays the general contour of simulated LMs in the process of changing their parameters by various algorithms. When button 14 “Save As” is pressed after the end of the VI operation (button 15 is pressed - “STOP”), the simulated LM signal is recorded to a file for subsequent retrospective analysis with experimental data.

For the analytical description of the brightness structure, the bounded piecewise continuous functions f(x) for each region fᵢ and the noise function n(x) are used:

\[
g(x) = \sum_{i=1}^{N} [f_i(x)]_{x \in \Omega_i} + n(x) .
\]

In this case, the task areas fᵢ may overlap, but they do not have gaps. The function g(x) has the contour width b localized in the area of its coordinate [x-b/2, x+b/2].

This model made it possible to obtain the measured distance using various algorithms based on the shape of the lighting distribution and the specified distance, that is, to determine the optimal algorithm for the parameters of the LM shape.

5. Building-up measurement algorithm
The difficulty of constructing the algorithm lies in the multiplicity of light markers in the observed field of view, the uncertainty of selecting the points for calibration, and the uncertainty of their range
parameters. In this case, it is necessary to determine the coordinates, shape and reliability of the data obtained. Therefore, in order to solve this problem, the Algorithm presented in Figure 2, implemented in the NI LabVIEW application is proposed using the macro functions of the NI Vision technical vision module.

The following algorithm includes input of image 1, converting the image in grayscale 2, selecting the reference points and setting of coordinate system 3, storing in memory 4, converting to binary image 5, for determining the LM sequence and their localization area 6, measuring on binary clusters LM 7. Retrieval from memory 8 returns the brightness structure in grayscale. Then brightness measurements 10 are made in each localization area. In this case, the built-in function is used as the main function. With weak localization and a sufficient size - algorithm based on a continuous wavelet transformation (CWT).

Figure 2. Light Marker Coordinate Algorithm

Comparing the results 11 enables to assess accuracy and reliability of measuring results of LM relative position. Comparison with the mathematical model (Figure 1) makes it possible to compare the relative position of the LM in pairs. If there is a discrepancy in the results, the parameter refining of the model relative to the shape of the LM is allowed.

6. Experimental research

To create a prototype hardware and software tool for controlling the light markers of the space observed by OES, an experimental stand was used (Figure 3). The stand consisted of: rack 1 (Bosch PTA 2400 0.603.B05.000); movable table 2 DREMEL 2600 (26152600KA); screen on support 3 (matte metal), size 177x235 mm²; linear slider 4; holder on suction cup 5 JOBY Suction Cup & Locking Arm; DC 6 Lytro ILLUM (Canon EOS M); Lens 7 Lytro ILLUM 9.5-77.8 mm 1:2 (CANON ZOOM LENS 18-55 1: 3.5-5.6); He-Ne 8 laser LGN-208B, power < 2.0 MW, polarization 1:1, TEM₉₀₀ spectral composition, beam diameter 0.6 mm, emission divergence 1.5 mrad; to determine the distance a BOSCH GLM 150 Professional laser meter, the minimum measurement distance of 5 cm, measurement accuracy of 1.5 mm, wavelength of 0.63 μm, was used.
Results of LM parameters determination by various algorithms are presented in Table 1. Experiment #1 refers to the laser emitter LGN-208B and the DC LYTRO, # 2 - to the DC Canon EOS M.

It can be seen from Table 1 that the brightness structure recorded by the LF DC has a more correct shape, which corresponds more to the actual brightness structure of the LM. As a consequence, the accuracy of measurement of its parameters by various algorithms (Table 2) has a smaller scatter and hence higher measurement accuracy. Greater accuracy of the LF DC during registration was given by a wider range of brightness displaying of the LM, which provided higher measurement accuracy (algorithm 1).

It can be noted that the LM image quality obtained by the LF DC, estimated by its fractality (Table 1, column. 6) [6], will be higher, i.e. more informative.

Table 1. Determination of LM parameters by various algorithms of DC 1 and LF DC.

|       | 2D Brightness structure | 3D Brightness structure | «Find Circular Edge» | «Circle Detection» | «Particle Analysis» | Image quality |
|-------|-------------------------|-------------------------|----------------------|-------------------|---------------------|---------------|
| DC LYTRO | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| DC Canon | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
Table 2. Measurement Results.

|                | LF digital camera | Regular digital camera |
|----------------|-------------------|------------------------|
|                | Algorithm 1       | Algorithm 2            | Algorithm 3          | Algorithm 1       | Algorithm 2            | Algorithm 3          |
| $X_C$          | 141.63            | 143.00                 | 143.11               | 145.46            | 144.00                 | 144.70               |
| $Y_C$          | 107.70            | 109.00                 | 108.30               | 108.97            | 108.00                 | 107.56               |
| $R$            | 23.20             | 10.28                  | 25.32                | 23.00             | 11.40                  |
| Dev            | 0.23              | -                      | 0.49                 | -                | -                      |

As experiments show, measurements in binary images strongly depend on the parameters of the algorithm, while in the brightness structure measurement algorithm the coordinates are less dependent on the parameters.

The most accurate measurement results can be given by the CWT algorithm, but it is dependent on the probability of gross error.

7. Conclusions

Studies have shown that the accuracy of measurement by various algorithms of relative coordinates of several laser emitter light markers for single-tone targets registered by the LF digital camera is several times higher (0.2 - 0.3 mm) than the accuracy of determining the light marks by a regular digital camera (DC). In addition, the LF digital camera has built-in calibration, which improves measurement accuracy as increasing the distance between LMs. For large magnifications of the optical image system, the LM has a larger size and information density, which allows increasing the accuracy by CWT algorithms. It can be concluded that in order to improve the coordinate measurement accuracy of the LM laser emitter by means of technical vision, it is advisable to preliminary select them according to the presented method of comparing with the mathematical model. For operation in a wide range of action for semiconductor laser emitters, it is advisable to use tunable graduated optics. In any case, the accuracy of determining the coordinates of LM with LF digital cameras will be more than 1.5 higher. However, they require considerable time to process the LF file. Using a smart camera allows creating ready-made solutions with high speed.

For detecting the LM of the laser emitter, as well as detecting small distant objects, it is advisable to use a telescopic system that allows obtaining a minimum viewing field of the optical system, that is, the maximum size of light reference marks on the surface of the sensor. However, the use of a telescopic system for recording from short distances is not feasible due to the small light power and distortion of the optical system.

Studies have shown that the use of digital cameras of the light field can be used to solve a wide range of problems solved by intelligent transport systems, such as highly accurate orientation and remote observation of objects with the determination of their parameters.

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