Phase triangulation method for measuring 3D geometry of complex profile objects under dynamic noise

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Abstract. The paper proposes a method of phase triangulation for measuring the three-dimensional geometry of complex objects under conditions of dynamic noise. The method is based on statistical analysis of experimental data, adaptive filtering and use of a controlled source of structured exposure. Theoretical and experimental estimates of the error by the proposed method are presented in the paper. The method allows a reduction in the measurement error of the three-dimensional surface geometry of complex objects using phase triangulation methods.

1. Introduction
The improvement of precision methods of non-contact measurement of linear dimensions is of great importance in the development of many fields of science and technology [1-3]. For non-contact measurements of the surface profile of three-dimensional objects, the most promising and well-developed are triangulation methods using structured lighting. They are based on illuminating the surface of an object with structured light and observing from a direction other than the direction of illumination. The observed 2D image, which is the spatial distribution of the intensity of light scattered by the object, contains distortions encoding information about the third coordinate. There are a large number of practical applications of optical-digital triangulation methods for industrial and scientific applications [1]. Moreover, in the literature there are works dedicated to triangulation measurements under industrial conditions [4]. Nevertheless, in existing developments, triangulation methods are used under specific conditions close to laboratory ones due to the use of small measuring bases, distancing measuring stands from production facilities and creation of comfortable working conditions.

A large number of works on optical-digital triangulation methods using structured lighting and phase triangulation to measure the three-dimensional surface geometry of complex objects are known [5-6]. A large number of works are dedicated to the issues of calibration of measuring systems [7-8], questions of optimization of measurement time and data processing [9-10], as well as issues of practical implementation and application [11-12].

However, the scientific and technical problem of creating digital optical methods for measuring the three-dimensional geometry of large-sized objects, applicable in industry, is currently not fully resolved. Existing high-precision measuring systems require almost laboratory conditions of use, impose stringent requirements on the light-scattering properties of the surface of the measured object, its three-dimensional profile and the conditions of external lighting for measurements [1]. For example, sunlight will introduce dynamic noise into the measurement path if the three-dimensional geometry of large objects is measured in variable cloudy weather. This is due to the fact that solar...
radiation scattered by clouds introduces difficulty predicted interference into the observed distribution of the intensity of scattered radiation on the surface of the measured object. On the other hand, measurements in an industrial room are also complicated by the influence of dynamic noise due to the used artificial lighting, the characteristics of which, as a rule, are not specifically studied. In addition, depending on the movements of products and equipment in the workshop, the structure of the light scattered on the measured surface can change dramatically. This leads to the fact that, depending on the parameters of structured illumination and characteristics of external lighting, the influence of introduced dynamic noise can vary from negligibly small to significant, making measurements impossible.

The aim of this work is the development of optical methods for measuring the three-dimensional geometry of complex objects based on phase triangulation to provide precision measurements in dynamic noise in the form of unsteady external lighting typical of industrial production.

2. Method description

The proposed method is based on the use of an excessive amount of experimental data from photodetectors, controlled spatio-temporal modulation of a structured optical source, and multidimensional digital analysis of experimental data.

As a result of applying this approach, the measurement process can be divided into several parts:
- collection of an excess of images of structured flare with various phase shifts. The values of phase shifts are set sequentially;
- assessment of the parameters of external lighting observed by the photodetector. Filtering images with incorrect recorded intensity;
- calculation of the intensity distribution function depending on the phase shift;
- calculation of the phase picture by a set of phase images;
- calculation of the measured surface profile using calibration data.

This approach assumes that during the measurement process and in the process of evaluating the parameters of external lighting, the controlled parameters will not change, and the background illumination parameters will change in accordance with the normal distribution. Filtering images with incorrect intensity involves a statistical analysis of the registered images and filtering by the sigma criterion.

Received images can be described by the following expression:

\[ I_n(x, y) = A(x, y)(1 + V(x, y) \cos(\varphi(x, y) + \delta_n)) + E(x, y, n), n = 0..N \cdot K, \]

where \( I_n(x, y) \) is the recorded intensity distribution in the phase picture, \( A(x, y) \) is the distribution of background intensity; \( V(x, y) \) is average visibility; \( \varphi(x, y) \) is the desired distribution of the phase difference encoding the information of the range of the object; \( \delta_n \) is introduced phase shift between adjacent images of structured flare; \( N \) is the number of shifts, \( K \) is the number of repetitions.

Further, given the correctness of the expression:

\[ \delta_n = \delta_{n+i+N}, n = 0..N, i = 0..(K - 1), \]

for each value \( i = 0..N \), a set is formed

\[ I_{n+k}(x, y) = A(x, y)(1 + V(x, y) \cos(\varphi(x, y) + \delta_n)) + E(x, y, n + kN). \]

Let us calculate the mean and standard deviation for each \( n \):

\[ \bar{I}_n(x, y) = \frac{\sum_{k=0}^{K-1} I_{nk}(x, y)}{K} \]  
\[ \sigma(x, y, n) = \sqrt{\frac{\sum_{k=0}^{K-1} (I_{nk}(x, y) - \bar{I}_n(x, y))^2}{K}} \]

We determine \( I'(x, y, n) \) by 2 sigma criterion:
\[ \{I^*(x, y, n)\} = \{I_{nk}(x, y), \forall k: |I_{nk}(x, y) - \overline{I_n(x, y)}| < 2 \cdot \sigma(x, y, n)\]  \hspace{1cm} (6)

We calculate \(I_n^*(x, y)\), as the mathematical expectation of the set \(\{I^*(x, y, n)\}\):

\[ I_n^*(x, y) = \langle I^*(x, y, n) \rangle \]  \hspace{1cm} (7)

The desired phase distribution \(\varphi(x, y)\) can be found using the expression:

\[ \varphi(x, y) = \arctan\left(\frac{\sum_{n=0}^{N} I_n^*(x, y) \cos(n\delta_n)}{\sum_{n=0}^{N} I_n^*(x, y) \sin(n\delta_n)}\right) \]  \hspace{1cm} (8)

Based on the assumption that dynamic disturbances recorded on phase images have a random distribution, it can be estimated that the proposed method allows a reduction in the measurement error in \(\sqrt{K}\) as compared to the classical phase triangulation method.

3. Experimental results

To test the operability of the proposed method for measuring three-dimensional geometry under dynamic noise conditions, we performed an experiment, when in addition to a structured illumination, radiation was additionally projected onto the measured surface with a random intensity distribution. The measurement scheme is shown in Fig. 1: 1 is the measured object, 2 is the LED projector that forms phase images on the surface of the measured object, 3 is the photodetector that records phase images, 4 is the LED projector that generates dynamic noise detected by the photodetector.

![Figure 1. The scheme of the experimental setup. 1 – measured surface, 2 – source of structured illumination, 3 – image receiver, 4 – source of random dynamic noise.](image)

During the collection of experimental data for each phase shift value, data were collected in the amount of 100 images, which were analyzed, filtered and average image \(I_n^*(x, y)\) was calculated according to expression (7). Next, the phase shift was calculated to restore the three-dimensional geometry of the surface of the object.

The Logitech C270 photodetectors were used in the experiment to analyze images with a resolution of 1024x768 pixels. An LED projector is used as a source of structured illumination, which provides image formation on the surface of an object with resolution of 800x600, contrast of 800: 1 and brightness of 800 lumens. Dynamic noise was created by a projector with brightness of 400 lumens,
located in a direction different from the direction of the structured illumination source and photodetector.

A flat sheet of cardboard was used as a measured object. Figure 2 shows an example of the analyzed image.

![Image](image_url)

**Figure 2.** An example of the analyzed image.

Figure 3 shows the dependence of $I_{nk}(x,y)$ on $k$ according to expression (3) for $x = 300$, $y = 400$, $n = 0$.

![Graph](graph_url)

**Figure 3.** Dependence of the observed intensity at the point $(300,400)$ at $\delta_n=0$ under random dynamic noise.
As a result of filtering by condition (6), the intensity distribution \( \{ I^*(x, y, n) \} \) is obtained. Figure 4 shows the dependence \( I^* \) for \( x = 300, y = 400, n = 0 \). The axis of the image in the set \( \{ I^*(x, y, n) \} \) is plotted along the X axis in the graph.

![Graph showing dependence of observed intensity](image)

**Figure 4.** The dependence of the observed intensity at the point (300,400) at \( \delta_n = 0 \) under conditions of random dynamic noise after filtering according to criterion 2 sigma.

Further, to obtain a phase picture and a three-dimensional cloud of points on the surface of the measured object, the mathematical expectation of the set \( \{ I^*(x, y, n) \} \) is calculated.

As it is mentioned above, the proposed approach reduces the measurement error under random dynamic noise by \( \sqrt{K} \) times. Thus, in the experiment, the error in measuring three-dimensional coordinates is reduced by a factor of 10 as compared with the decoding of phase images by the classical method.

**Conclusions**

The method of phase triangulation proposed in this work for measuring the three-dimensional geometry of complex-profile objects allows high-precision measurements under the conditions of existing industrial technologies. Theoretical and experimental estimates of the error by the proposed method are presented. It is shown theoretically and experimentally, that the proposed method allows a reduction in the measurement error in \( \sqrt{K} \) as compared to the classical phase triangulation method. The obtained technical solutions are distinguished by their universality of application and can be used to measure geometric parameters in a wide range of practical applications in scientific research and industrial technologies.
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