Adaptive Control of the Spatial Modulation Frequency in the Phase Triangulation Method

Sergey V. DVOYNISHNIKOV*, Grigoriy V. BAKAKIN, Dmitry V. KULIKOV, Vladimir A. PAVLOV and Oleg Yu. SADBAKOV
Kutateladze Institute of thermophysics SB RAS, Novosibirsk, Russia
*Corresponding author

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Abstract. The method for determining the optimal frequency of spatial modulation in the measurement of three-dimensional geometry by the method of phase triangulation is proposed. The method is based on the construction of the frequency response of the measuring system. The proposed approach makes it possible to use the optimal frequency of spatial modulation of an optical source in measurements of three-dimensional geometry by the method of phase steps and the Gray binary code. As a result, this method makes it possible to create a universal control algorithm that provides measurement of three-dimensional geometry by the method of phase steps with the smallest error.

Introduction

Methods for measure geometry of complex three-dimensional objects based on the triangulation principle using phase-structured lighting are actively developing and improving [1].

In the phase triangulation method, phase error depends on the number of phase images $N$ and the relative error of the photodetector $\frac{\Delta I}{I}$ [2]:

$$\Delta \varphi = \Delta I \sqrt{\frac{1}{N}}$$

(1)

The error of measuring $Z$ coordinate (the depth of the scene) according to [4] can be estimated:

$$\Delta z = \frac{\Delta \varphi \cdot p}{2\pi \cdot \tan \theta} = \frac{\Delta I \cdot p}{2\pi \cdot I \cdot \sqrt{\frac{1}{N}} \cdot \tan \theta},$$

(2)

where $p$ is a period of spatial modulation of optical radiation, $\theta$ is a triangulation angle.

It follows from expression (2) that the error of $z$ coordinate measuring is proportional to the period of spatial modulation of the optical radiation. That is, to minimize measurement error in the phase triangulation method, it is necessary to minimize the period of spatial modulation of optical radiation.

Obviously, as the period of spatial modulation of the radiation decreases, the measurement range of phase triangulation method also decreases. Phase values can be uniquely recovered only within the period. To increase the measuring range, various methods for deploying the phase field are used. These methods are actively used in interferometry. There are known phase-field expansion algorithms, where priori data about the object under investigation is used to determine the total phase, i.e. number of full periods [3]. Algorithms for reconstructing the total phase with integer analysis are known. Such methods expose an object by a series of phase images with different multiple periods of spatial modulation of optical radiation [4]. The most promising methods for triangulation measurements with structured light illumination are the methods of extending the measuring range using phase steps and binary coding of pixels [5-7]. This approach ensures the best measurement accuracy when projecting the least amount of structured images.

In reality, there are restrictions on the spatial resolution of the image, which is formed by the optical system. Due to the aberration distortion of the optical elements of the measuring system, the limited depth of field of the source and the receiver of optical radiation, it is impossible to obtain an absolutely sharp image. Therefore, it is necessary to select the frequency of spatial modulation of
optical radiation based on the following considerations. On the one hand, the radiation frequency should be less than the frequency of the equivalent low-pass filter, which is the optical system of the measuring device. On the other hand, the frequency must be as large as possible to ensure a minimum measurement error.

As a rule, this problem is solved by direct choice of the spatial modulation frequency in the design of the measuring system. This approach will be quite effective when measuring uniform objects with the same measurement parameters. However, if necessary, to provide high-precision measurements of complex objects freely oriented in space, this approach can become a source of additional measurement errors.

A method for estimating the optimal spatial modulation based on the spatial frequency analysis of the image observed by the photodetector is known [8]. The method is quite laborious and if the choice of structural lighting is unsuccessful, it may give an inaccurate estimate of the optimum frequency.

**Method Description**

In this paper, another method to estimate the optimal frequency of spatial modulation is proposed. The method consists of performing a four-step measurement procedure: at the first step, images encoding the horizontal coordinate of the reflective Gray binary code are formed on the surface of the measured object; at the second step, the optimum frequency of spatial modulation is determined based on obtained images; at the third step, phase images are formed with an optimum spatial modulation frequency; at the fourth step, the phase shift is calculated and the phase is expanded based on the measurement results by the Gray code.

The estimation of the optimal frequency of spatial modulation was carried out as follows. For each Gray code exposure the average observed amplitude of the radiation source is calculated. For this purpose, a black-and-white image is projected onto the surface of the measured object, corresponding to the current step of the algorithm and its negative: an image where white bands are formed instead of black bands, and black ones instead of white ones. The average amplitude is determined by the formula:

\[
A_i = \frac{\sum_x \sum_y |G_i(x,y) - G^*_i(x,y)| \delta_i(x,y)}{\sum_x \sum_y \delta_i(x,y)},
\]  

where \(G_i(x,y)\) – is the observed brightness on the image at the point with coordinates \((x,y)\) when projecting the illumination encoding \(i\)-th step of Grey-code sequence. \(G^*_i(x,y)\) – is the observed brightness on the image at the point with coordinates \((x,y)\), when projecting negative of illumination encoding \(i\)-th step of Grey-code sequence. \(\delta_i(x,y)\) is a function that determines whether the photodetector sees at a point with the \((x, y)\) coordinates from the projector:

\[
\delta_i(x,y) = |G_i(x,y) - G^*_i(x,y)| > N,
\]

where \(N\) is the threshold determined by the noise level on the observed images.

Further, dependence function of the average amplitude of the observed illumination of the spatial modulation frequency is formed:

\[
F_i = \frac{1}{\tau_1} = \frac{2^i}{N},
\]

where \(N\) is the horizontal resolution of the projector. Period of spatial modulation in the Gray code is equal to the power of the 2 of ordinal of the illumination pattern. The obtained dependence \(A(F)\) is the amplitude-frequency characteristic of the source-receiver path of the optical radiation of the measuring system.

From the dependence obtained, we form the regression curve and determine the modulation frequency \(F^{opt}\), when observed amplitude of the illumination will correspond to the expression \(A(F^{opt}) = L\). The parameter \(L\) determines the minimum amplitude level exceeding the noise amplitude on the recorded phase images. Its value is chosen based on the measurement conditions and the characteristics of the used optoelectronic components.
Experimental Results

An experimental demonstration of the proposed method was performed. Figure 1 shows the registered images of the structured illumination with the Gray code in steps 5 and 9.

![Figure 1](image1.png)

Figure 1. An example of a structured illumination observed by a photodetector with Gray code in step 5 (a) и 9 (b).

![Figure 2](image2.png)

Figure 2. The obtained amplitude-frequency characteristic of the source-receiver path of optical radiation (A) and noise level.

As a result, the frequency of spatial modulation of 0.12 Hz is chosen. Figure 3 shows the obtained dependence of the observed horizontal coordinate of the projector as a function of the coordinates of the point on the photodetector. The measurements were carried out using phase images with a spatial frequency of 0.12 Hz, which corresponded to the period of the harmonic signal at the radiation source of 52 pixels.

![Figure 3](image3.png)

Figure 3. Dependence of the observed horizontal coordinate of the projector as a function of the coordinates of the point on the photodetector.

It can be seen that in areas falling into the shadows and not receiving illumination from a source of structured illumination, the results were in the form of random noise.
Figure 4 shows a section of the image in fig. 3 at a height of 150 pixels showing the smooth character of the obtained curve. The noise level was about 0.5% of the measuring range, which is very high, given the poor quality of the used optoelectronic elements of the measuring system.

Conclusion

A method for determining the optimal frequency of spatial modulation in the measurement of three-dimensional geometry by the method of phase triangulation is proposed. The method is based on the construction of the frequency response of the measuring path from the data obtained in the process of the formation of light illumination realizing the Gray code. The proposed approach makes it possible to use the optimal frequency of spatial modulation of an optical source in measurements of three-dimensional geometry by the method of phase steps and the Gray binary code. As a result, this method of measurement makes it possible to create a universal control algorithm for measuring system that provides measurement of three-dimensional geometry by the method of phase steps with the smallest error.

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References
