Software package for testing three-dimensional shape measurement methods using structured lighting

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Abstract. This work aims at creating a universal software package for the development and testing of triangulation methods using structured lighting for measuring the three-dimensional geometry of objects in difficult ambient lighting conditions. As a result, a software package meeting the stated requirements is created. Lighting is based on the Fong model. A method for preloading objects is implemented to optimize the operation of the software package. An accelerated method for creating shadow maps is proposed and implemented. The developed software package is shown to successfully perform all required functions.

1. Introduction
The solution of many urgent problems in science, industry, medicine and other fields requires the development and creation of highly efficient systems for measuring the three-dimensional geometry of objects [1]. This need is strongly manifested in various industries. Note that modern industrial production is largely automated, which is caused by the need for a quick response to changes in the market and a change in the range of products, as well as the need to reduce the cost of products. Such a situation incites an increasing relevance of quality control systems, on which the requirements of high accuracy and speed are imposed. Most of these systems are occupied by devices for controlling geometric parameters, which determines the need to create systems for measuring three-dimensional geometry of an object. Triangulation methods using structured lighting [2–4] are of particular importance in view of the optimal characteristics when measuring at distances from several centimeters to several meters and a number of distinctive properties: the possibility of using various structured illumination for specific tasks, the ability to select the optimal parameters of triangulation in a specific task, simultaneous scanning of the entire scene and, therefore, the ability to measure dynamically moving objects [5–7]. The above facts make triangulation methods using structured lighting the most promising for solving a number of pressing scientific problems: measuring the geometric parameters of dynamic objects in phase-inhomogeneous media, measuring the three-dimensional geometry of large objects, etc. However, the emerging spectrum of scientific and technical problems in optics, radiation sources, photo registration and signal processing determines the relevance of the development and testing of triangulation methods using structured lighting.

The problem described above implies the need for a software package for testing and developing triangulation methods for measuring the three-dimensional geometry using structured lighting. This software package will serve as a tool for the development and testing of data processing algorithms for measuring three-dimensional geometry by triangulation methods using structured lighting. This will speed up the selection of the optimal triangulation method using structured lighting for a specific task, the selection of optimal parameters for multiparameter triangulation, the development of triangulation methods using structured lighting due to saving time and money for preparing a real experiment. The
aim of this work is to create a universal software package for the development and testing of triangulation methods using structured lighting for measuring the three-dimensional geometry of objects in difficult ambient lighting conditions.

2. Defining the task
To achieve this goal, it is necessary to solve a number of problems: to provide the ability to simulate the process of measuring the three-dimensional geometry of an object by triangulation methods using structured lighting, to provide the ability to flexibly adjust the parameters of objects on a three-dimensional scene, to develop and implement a method for modeling shadows on a three-dimensional scene. Thus, the main requirements for the developed software package are:
- adding external light sources to the scene;
- flexible setting of external light sources;
- adding a source of structured lighting to the scene based on sinusoidal stripes;
- adding arbitrary structured illumination to the projector scene;
- loading the object model from an external file;
- flexible adjustment of parameters of objects on the scene;
- implementation of shadows;
- work in the modes of scene formation and experiment.

Modeling of light scattering by the object surface, the classical Fong model is applied, which provides for the presence of specular and scattered light scattering. The specular component of illumination at a point on the surface is described by the expression:

\[ I_s = I_{\text{incident}} * k_s * (\cos(R, V))^\alpha \] (1)

where \( I_{\text{incident}} \) is the intensity of the incident light, \( k_s \) is the specular reflection coefficient (material property), \( R \) is the direction of the beam in the case of perfect reflection, \( V \) is the direction towards the observer (from a point at the interface), and \( \alpha \) is the gloss coefficient (material property).

Taking into account the Lambert's law that the intensity of radiation from a radiating surface with a direction-independent radiation brightness is directly proportional to the cosine of the angle between the direction of the observer and the normal vector to the surface, the scattered illumination component at a point in the Fong reflection model is described by the expression:

\[ I_d = I_{\text{incident}} * k_d * \cos(N, V) \] (2)

where \( I_{\text{incident}} \) is the intensity of the incident light, \( k_d \) is the property of the material to perceive diffuse illumination, \( N \) is the direction of the normal to the surface, and \( V \) is the direction towards the observer (from a point at the interface).

The Fong model also takes into account the presence of background lighting. The background component at a point is described by the expression:

\[ I_a = I_{\text{ambient}} * k_a \] (3)

where \( I_{\text{ambient}} \) is the intensity of the background lighting, and \( k_a \) is the property of the material to perceive the background lighting.

Thus, the final intensity at a point is described by the expression:

\[ I_{\text{point}} = I_{\text{emission}} + I_a + \sum(I_{di} + I_{si}) \] (4)
where $I_{\text{emission}}$ is the intensity of the light emitted by the material, $I_a$ is the background component, $I_{di}$ is the scattered light component from the i-th light source, and $I_{si}$ is the specular component from the i-th light source.

The implementation of shadows on a three-dimensional scene is based on the construction of a shadow map. In each direction of the light source emission, the distance from the light source to the nearest object is measured and stored. Thus, to determine the illumination of a point, it is necessary to iterate over each light source and check whether the distance from the current source to the point is less than or equal to that recorded in the shadow map for the given direction. If the answer is positive, the point is illuminated by the current light source.

For the formation of complex illumination of a three-dimensional scene, support for various types of light sources is implemented: a point source, a unidirectional source with parallel beams, a structured illumination projector, and an arbitrary illumination projector. The user has the ability to adjust the operating time of various light sources and lighting parameters: position, orientation, intensity, attenuation, blinking period, horizontal and vertical viewing angles.

The imitation of the process of measuring the three-dimensional geometry of the object surface is based on the support of the flexible functionality of the camera: registration, saving, changing the resolution of scene images; moving the camera.

3. Software testing

Software package for testing three-dimensional shape measurement methods using structured lighting was implemented using C++ language. OpenGL library was used for rendering 3D scenes. User interface was implemented using WinAPI library.

Testing of the created software package was carried out. A number of experiments were performed using the method of phase steps and the calibration method, and a set of images was obtained to reconstruct the phase distribution and three-dimensional geometry of the object. Fig. 1 - 5 show the results of testing the created software package on various scene configurations. Figure 1 shows the simulation testing of the light scattering properties of the object surface.

![Figure 1](image1.png)

**Figure 1.** Testing the modeling of the light-scattering properties of the object: a) the material of the object is bronze; b) the material of the object is gold; c) the material of the object is copper; d) modeling object material (bronze) and texture radiation.
Fig. 2 shows the results of testing external light sources: unidirectional light source with parallel beams; point omnidirectional light source; a light source of the "flashlight" type.

Fig. 3 shows the results of testing of simulated projectors. Below one can see the operation of a structured lighting projector at different values of the initial phase (a, b), an arbitrary structured illumination projector at different distances from the object (c, d), a projector with parallel beams at different distances to the object (e, f).

Figure 2. Simulation testing of external light sources: a) unidirectional light source with parallel beams; b) point omnidirectional light source; c) a light source of the “flashlight” type.

Figure 3. Testing the modeling of projectors: a, b – a structured lighting projector with parallel sinusoidal stripes (changing the phase of the sinusoid by $\pi / 2$); c, d – an arbitrary structured illumination projector (changing the distance to the object); e, f – a projector with parallel beams (changing the distance to the object).

Figure 4 demonstrates testing of shadow modeling: applying a rectangular shadow map (a) and applying a spherical shadow map (b).
Figure 4. Shadow modeling testing: a) a shadow from a unidirectional light source with parallel rays; b) shadow from a point omnidirectional light source.

Figure 5 shows the results of simulating the process of measuring the three-dimensional geometry of various surfaces: with a convex curvature of the surface and the applied texture on the surface of the object.

Figure 5. Modeling the application of the phase steps method. A - the surface of an object with a texture and various phase shift of the projector image; b - the convex surface of the object and various phase shift of the projector image.

Comprehensive testing of the created software package for testing and developing triangulation methods using structured lighting for measuring the three-dimensional geometry of an object in difficult lighting conditions has been carried out. The modeling of the light-scattering properties of the object surface, external light sources, the formation of shadows, the application of the method of phase steps has been tested. The testing task has been solved by running a number of scene configurations. The realized tests demonstrate the correct operation of the created software package.

Conclusions
As a result, a software package meeting the stated requirements has been created. Lighting is based on the Fong model. A method for preloading objects has been implemented to optimize the operation of the software package. An accelerated method for creating shadow maps has been proposed and implemented. Comprehensive testing of the created software package for testing and developing triangulation methods using structured lighting for measuring the three-dimensional geometry of an object in difficult lighting conditions has been carried out. It is shown that the developed software package successfully performs all the required functions.
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