Universal Industrial-applicable Calibration Method of Optical-electronic Triangulation Systems for 3D Geometry Measurements

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Abstract. Universal industrial-applicable calibration method for optical-electronic triangulation systems using structured illumination for 3D geometry measurements is proposed. An analytical and experimental estimations of the measurement error due to the method of phase steps and system calibration were obtained. The method has a simple implementation when measuring the 3D geometry of large objects. It is shown, that proposed method can be effectively used in measurement systems constructed on a standard low-cost element base.

1. Introduction
The development of methods for measuring 3D geometry of complex-profile objects is very important for the modern industrial production technologies [1-2]. The most promising are optoelectronic methods for measuring geometric parameters. Calibration of optoelectronic systems for measuring 3D geometry consists in determining a set of parameters describing the mapping of 2D coordinates of a spatial modulator of an optical source on spatial 3D coordinates in which the measured object is located (world coordinates); and the mapping of world 3D coordinates, in which the measured object is located, on the 2D coordinates of the image of the detector of optical radiation. We can determine the three-dimensional coordinates of a point in the world coordinate system, having received coordinates of the point of the measured object on the image of the detector and knowing the corresponding coordinates in the plane of the projector. Unlike calibration of robotic arms or automated trolleys, the calibration methods proposed and used in this work are static. Calibration is performed once and after that it will be reliable as long as the relative position of the detector and the projector remains unchanged.

In measurement systems using spatially modulated sources of optical radiation, calibration is an extremely important task. Recovery of complete information about the surface geometry is possible if the optical parameters of the detector and the projector of optical radiation are known in the global coordinate system. As a rule, methods for calibrating active-type vision systems are more complex than methods for calibrating passive-type systems, such as stereovision systems.

Most widely used standard technical solution of calibration [3-5] is associated with the execution of a 3-step procedure. These are the determination of the internal parameters of the detector, the determination of the internal parameters of the projector and the determination of the geometric parameters of the Euclidean transformation associated with the projector and detector of optical radiation.

In most works, when determining the internal parameters of the projector and detector of optical radiation, the authors use approximations of geometric optics, which do not take into account the...
distortions caused by defects and aberrations of optical elements. When using systems in laboratory conditions and using high-quality low-aperture optics, errors associated with optical aberrations will be negligible, but when implementing measurements in industrial technology, they must be taken into account due to the presence of non-stationary phase-inhomogeneous distortions.

2. Method Description

To solve this scientific problem, a method of calibrating an optoelectronic system for measuring 3D geometry has been proposed. Proposed method involves to use a calibration object, which is a vertical rail on a stand, stable in a vertical position (fig. 1). On the rail there are calibration targets in the form of circles. The rail is moved in the horizontal plane and the dependence of the coordinates of the targets on the images, the magnitude of the phase shift of the probe sinusoid and the Cartesian coordinates of the targets in the global coordinate system are memorized.

After measuring and remembering the required number of points in space, based on the data obtained, a regression function is constructed depending on the 3 Cartesian coordinates in the global report system on the magnitude of the phase shift and the coordinates of a point in the image

\[(X, Y, Z) = F(X_c, Y_c, P_p)\]  

(1)

After that, the target object is measured: the phase shift value is measured for each point on the image of the object and the Cartesian coordinates are determined in the global coordinate system for each image point of the object using the obtained regression calibration function.

The relative measurement error caused by the calibration error using the calibration procedure can be estimated as

\[\Omega = \frac{\delta}{\sqrt{M}},\]  

(2)

where \(\delta\) is the measurement error of the Cartesian coordinates of the calibration object, \(M\) is the number of measurements of the calibration object with different Cartesian coordinates, \(X_c\) is the resolution of the horizontal component of the optical detector, \(Y_c\) is the resolution of the vertical component of the optical detector.
The total relative error of measurement of Cartesian coordinates can be estimated from above as a sum of $\theta$, $\Omega$ and an additional error due to the image resolution obtained by using an optical detector:

$$\Omega = \frac{\Delta I}{\sqrt{NI}} + \frac{\delta}{\sqrt{M}} + \frac{1}{X_{e}}. \quad (3)$$

The obtained analytical error estimation allows us to estimate the relative measurement error of the 3D geometry of large-sized objects by triangulation methods using structured lighting. Let the relative error of measuring the brightness of the radiation in the path of projector - detector of optical radiation does not exceed 0.0078 (this error is due to the use of an LCD projector, the color coding depth of which is 8 bits). Let in our implementation of an optoelectronic measuring system the number of radiated highlights having a different initial phase shift, $N = 1000$. Let the relative error of measurement of the Cartesian coordinates of a point in the calibration process $\delta = 0.1\%$. The number of points of the calibration object involved in the calibration $M = 200$. Let the resolution of the images received by the receiver of optical radiation is 3000x2000 pixels (such resolution is provided by standard digital cameras). Then, the total relative error of measurement of 3D geometry of methods based on optical triangulation using structured radiation can be estimated from above as

$$\Omega = 0.00024 + 0.00007 + 0.0005 = 0.00081 = 0.081\%. \quad (4)$$

3. Experimental Results

An experimental implementation of the proposed universal calibration method was performed. The calibration target is a vertical rail with reference marks located on it. As a result of the calibration, a set of points in space is formed, corresponding to the reference marks that fall into the camera's sector of view and illuminated by a projector.

To simplify the task of determining the 3 Cartesian coordinates of the reference marks, it is assumed that the OZ axis is located vertically, and the OX and OY axes are horizontal and orthogonal to each other.

To solve the problem of determining the Cartesian coordinates of the reference marks in the world coordinate system, the rail is mounted vertically using a vertical plumb located on a calibration target. After that, the distance from the reference targets to the point of intersection of the vertical bar of the calibration target and the plane $Z = 0$ is measured. This determines $Z$ coordinates in the world coordinate system for the reference marks (since the rail axis is parallel to the OZ axis). After that, it is necessary to calculate the Cartesian coordinates of the vertical bar of the calibration target in the horizontal XY plane. To solve this problem, measurements of distances in the XY plane are carried out.

![Figure 2. Measured wall fragment (circled in white frame).](image)
The calibration of the measurement system that implements the optical triangulation method with structured lighting has been performed. According to the results of 45 measurements of the calibration target, it was found that the RMS error in determining coordinates X, Y, Z is about 5 mm. The linear size of the measuring volume was about 1 meter, the relative error of about 0.5%. The error was determined by comparing the coordinates measured manually by the experimenter and measured by the system. This error characterizes the total error in determining the coordinates of the calibration target during calibration.

To assess the accuracy of measurements of three-dimensional geometry, the system conducted an experiment to measure the 3D geometry of a flat surface of a room wall. In fig. 2 in the white frame shows the measured fragment of the wall.

Figure 3 shows the measured 3D wall geometry. The relief charts clearly show the electrical outlet in the lower right corner of the wall fragment.

Figure 3. Measured 3D wall fragment geometry.

Figure 4 shows the cutoff deviation along the line Z = 400 mm of the measured 3D geometry of the fragment of the wall from the straight line.

Figure 4. Deviation of the cut Z = 400 mm of the measured 3D geometry of the wall fragment from a straight line.
The standard deviation of the curve shown in Fig. 4 is 1.14 mm. This means that the relative measurement error obviously does not exceed the level of 0.057%.

4. Conclusion
Universal industrial-applicable calibration method for optical-electronic triangulation systems using structured illumination for 3D geometry measurements is proposed. The method has a simple implementation when measuring the 3D geometry of large objects. An analytical and experimental estimations of the measurement error due to the method of phase steps and system calibration were obtained. It was less than 0.1% of the range of measured values when implemented on a standard low-cost element base.

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