Calibration error minimization method of three-dimensional geometry optical meter with two photodetectors

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Abstract. The paper presents a method for minimizing the calibration error of a triangulation three-dimensional geometry meter with two photodetectors, ensuring a reduction in the calibration error using the method of an arbitrarily oriented flat calibration object in the measuring volume. The method is based on minimizing the deviation from flatness of the result of the reconstruction of a three-dimensional image of a calibration object and can be used in the algorithm for automatic calibration of a triangulation meter of three-dimensional geometry with two photo-receivers.

1. Introduction
Three-dimensional measurements of the shape of physical objects are widely used in many areas of hydro and aerodynamic research [1]. The problem is solved with the use of contact, on the basis of coordinate-measuring manipulators and probes, as well as contactless triangulation methods. Contact methods are relatively simple to implement, but have a number of obvious defects and limitations.

In optical triangulation methods the measured object is illuminated by a structured source of optical radiation and observed from a direction other than the direction of illumination [2–4]. On the observed image there are distortions, which encode information about the distance from the light source to the object. This paper considers a combined modification of a triangulation meter that uses two photodetectors and an optical radiation source to form a structured illumination. This combination allows you to shoot the measured object from different angles and solves several problems at once: the projector allows to solve the problem of blind zones; structured light allows to simplify searching of conjugate points on measured object images.

Conjugate points on the images of the measured object from two photodetectors allow to perform triangulation to restore the three-dimensional coordinates of the points presented in both images. In order to carry out triangulation, it is necessary to calibrate the measuring system, that is, to determine the values of the parameters of its model. In general, the camera has internal and external parameters. Also, in the case of two cameras, it is necessary to know the offset of one camera relative to another.

Calibration is targeted to estimate the implemented internal and external parameters of triangulation. Various calibration methods are known, but 3-dimensional calibration reference object and calibration plane are mainly used.

The example of calibration with planes is the method presented in [5]. The method allows you to calibrate the receiver of optical radiation without specialized calibration devices, to obtain the internal and external parameters of the optical system, as well as image distortion factors. In this case, a flat surface is used as a calibration object.
Calibration uses the classic pinhole camera model. The relationship between the 3D point \( M \) and its projection on the image \( m \) is given by the formula:

\[
sm = A[R \ T]M = PM,
\]

(1)

where \( s \) is an arbitrary scale factor, \((R, t)\) are external parameters: rotation and translation, which link the spatial coordinate system with the camera coordinate system, and \( A \) is the matrix of internal camera parameters. A projection transform is constructed between the model plane and its image, after which restrictions are imposed on the internal parameters of the camera. Then, based on the constraints, two homogeneous equations are written, whose solution is refined using the maximum likelihood method.

\[
A = \begin{bmatrix}
f_x & \gamma & u_0 \\
0 & f_y & v_0 \\
0 & 0 & 1
\end{bmatrix},
\]

(2)

\[
P = A[R \ T],
\]

(3)

To estimate the calibration error in the method, the difference between the coordinate of the 3-dimensional point on the image and its projection on the same image using internal and external parameters is used. Evaluation is performed in pixels and does not carry metric information. This assessment is not objective because of use the same data as in the calibration.

Another disadvantage of this method of error estimation is random deviations (Fig. 1) of calibration data, which prevent the exact calculation of the parameters of photodetectors. As a result, the calibration error increases with an increase in the number of images of the calibration object (Fig. 2).

Figure 1. Example of distortion during calibration.
Figure 2. The dependence of the calibration error on the number of calibration images based on the analysis of coordinates of a point in the image and its projection.

This paper proposes a method to minimize the calibration error, taking into account the geometric shape of the calibration object.

2. Method description

Since it is known that the shape of the calibration object is described by a plane in space, the standard deviation of the coordinates of the calibration pattern from the equation of the plane can be used to estimate the calibration error:

\[ Z_i = (d - aX_i - bY_i)/c \]  \hspace{1cm} (4)

\[ \text{error} = \sqrt{\frac{\sum_{i=1}^{n}(Z_i - \bar{Z}_i)^2}{n}} \]  \hspace{1cm} (5)

where \( a, b, c, d \) are plane equation coefficients; \( X_i, Y_i \) are reconstructed surface coordinates of the calibration object; \( \bar{Z}_i \) is 3rd coordinate, calculated from the equation of the plane; \( n \) is a number of points.

Using the new criterion allows to enter a delayed subselection of images of the calibration object, which will be used to estimate the error.

The search algorithm consists of the following steps.

1. The selection of calibration images is divided into calibration subselection (the number of images \( K \)) and delayed subselection for error minimization procedure. Delayed subselection of the images is not involved in the calibration coefficients calculation, but it is used to objectively estimate the calibration error.

2. An initial calibration is performed for all calibration images and an estimate of the error in the delayed data.

3. \( K \) subselections are created with size \((K - 1)\). Each of these selection are lacked a unique pair of calibration images.

4. Calibration and error estimation is performed on \( K \) samples.

5. If the smallest error among the samples is larger than the initial one, the algorithm is completed.

6. If the parameter \( K \) has reached its minimum value (4 images), then algorithm is completed with an error - the calibration data is invalid. It is necessary to repeat the collection of calibration data again.
7. Otherwise, the sample with the smallest error becomes the calibration sample, and the initial value of the error becomes equal to the sample error. The algorithm is repeated from step 3.

The algorithm works as long as any subset of the calibration data gives a calibration result worse than the calibration based on the entire set obtained in the previous step of the algorithm. The described algorithm allows to exclude outliers from the calibration data and achieve the minimum calibration error.

![Figure 3](image)

Figure 3. Calibration error depending on the number of calibration object images used

The proposed method minimizes the calibration error of a triangulation meter of three-dimensional geometry based on the use of two photodetectors and a source of structured illumination (Fig. 3). A measurement error of 1% is achieved for the measurement system with low resolution cameras.

Conclusion

The paper presents a method for minimizing the calibration error of a triangulation three-dimensional geometry meter with two photodetectors, ensuring a reduction in the calibration error using the method of an arbitrarily oriented flat calibration object in the measuring volume. The method is based on the analysis of flatness of the result of reconstruction of the three-dimensional image of the calibration object and allows you to implement an algorithm for automatic calibration of the triangulation meter of three-dimensional geometry with two photodetectors.

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