Circular Coded Target and Its Application to Optical 3D-Measurement Techniques*

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One of the primary but tedious tasks for the user and developer of an optical 3D-measurement system is to find the homologous image points in multiple images - a task that is frequently referred to as the correspondence problem. With the solution, the error-free correspondence and accurate measurement of image points are of great importance, on which the qualitative results of the succeeding 3D-measurement are immediately dependent. In fact, the automation of measurement processes is getting more important with developments in production and hence of increasing topical interest. In this paper, we present a circular coded target for automatic image point measurement and identification, its data processing and application to some optical 3D-measurement methods.

1 Introduction

At the moment, basic software and hardware components that are capable of constructing an optical 3D-measurement system are available on the market, and provide numerous combinations of measurement principles and methods, thus making possible the construction of a special or general purpose measurement system. Beside the software and hardware components any point target for the 3D-measurement is also considered as a part of the measurement system, since the overall measuring performance and the resulting accuracy levels are directly linked to the quality of center point determination. In addition, the measurement procedure of image points has blocked the automation and hence general acceptance of the optical 3D-measurement techniques in industrial applications.

In recent years, the demand for a *coded target* guaranteeing automatic error-free correspondence and accurate image point measurement has been dramatically increased [1,3-9]. Until now, some coded targets are accepted more or less for the industrial application of optical 3D-measurement techniques [2-9] (fig. 1). To realize fully automatic 3D-measurement procedures and an accurate image point measurement, we have developed a new circular coded target [10] (fig. 2), and have found an absolute acceptance from industry even in the toughest application of the coded target with superimposed random pattern [11]. In this paper, we intend to describe the geometric construction of the target, its image processing and application to some 3D-measurement methods.

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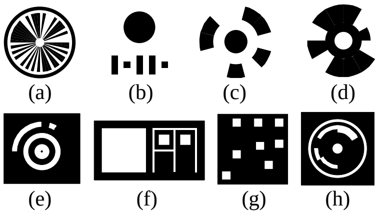


Fig. 1 Various types of coded target:
(a) Trenkler, 1981; (b) Wong, 1988;
(c) Schneider, 1991; (d) Knobloch, 1992;
(e) van den Heuvel, 1992; (f) Homainejad, 1995; (g) Fraser, 1997; (h) Niederöst, 1997.

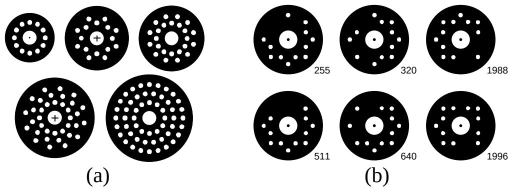


Fig. 2 The proposed circular coded target (Ahn, 1998): (a) Examples with 12-, 16-, 24-, 36- and 54-bit code length; (b) Coding examples of the 16-bit circular coded target with 12 turned on coding points and 2 coding layers. The bit position 0 (upper center) is the parity bit, and 2, 6, 10 and 12 (clockwise) are turned on always.

2 Geometric construction

Out of consideration for a robust and reliable image processing, the target is geometrically constructed only of circular elements, i.e. circular point mark, circular coding points and circular background plate (fig. 2). The superiority of the circular object target over other geometric features for the purpose of image point measurement is also reported in the literature [12]. The identification number of the target is coded down into the circular arrangement of the coding points around the point mark. Additionally, the size and arrangement of the coding point around the point mark are also geometrically prescribed (fig. 3b-3e). We have fully utilized all these geometric constraints on the target construction with the image processing, and have achieved a very robust and reliable image point measurement and identification.

3 Image processing

To minimize the necessary computing costs, binary image processing is preferably applied here, except the subpixel accurate edge detection of the contour points of the point mark. First, we know from the given imaging conditions the approximate size of the image ellipse of the used point mark (fig. 3a), assuming that an image ellipse is the projection of an object circle onto the image plane. In addition, such an image ellipse is a relatively compact image feature for a natural scene, where the compactness can be represented by the *form factor* as in equation (1).

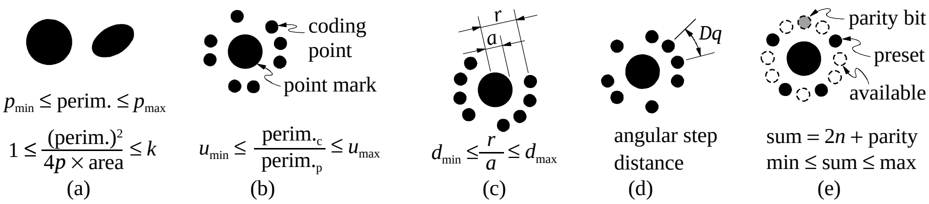
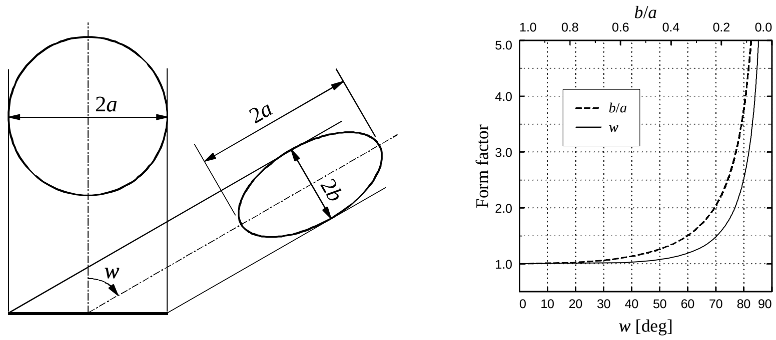


Fig. 3 Geometric features of the circular coded target: (a) Size and form factor of the point mark; (b) Normalized size of the coding points against the point mark; (c) Normalized distance of the coding points from the center of the point mark; (d) Angular step distance of the coding points; (e) Total sum and preset pattern of the bit positions including the parity bit.



(a) (b)

Fig. 4 Form factor of an image ellipse: (a) Ellipse as the image of an object circle assuming a parallel projection; (b) Dependence of the form factor on the projection angle.

$$\text{Form factor} = \frac{(\text{perimeter})^2}{4p \times \text{area}} \tag{1}$$

The form factor of an ellipse, the image of an object circle, increases with the imaging angle monotonously and moderately up to 1.5 at the angle of 70° (fig. 4). Thus, if we put bounds to the size and form factor of image objects (fig. 3a), we can detect all point mark candidates in the image plane, whose validity will be individually qualified in the subsequent processing steps. Next, around a point mark candidate we search for smaller image objects as the coding points of the point mark satisfying the membership criteria (fig. 3b-3c). After a proper coordinate transformation, an inverse affine transformation by using the 5 ellipse parameters of the point mark, we may obtain the reconstructed coded target (fig. 5). Through a certification and interpretation of the arrangement of the coding points (fig. 3d-3e), we will get the identification number of the target. A simplified work flow of the image processing for the circular coded target is given in fig. 6.

For an accurate image point measurement of the point mark and for a reliable rearrangement of the coding points (see fig. 5), an accurate estimation of the 5 ellipse parameters, e.g. ellipse fitting, of the image point mark is inevitable. Here we have applied an *orthogonal distances ellipse fitting* [13], which has an objective function of the orthogonal error distances and results in an unbiased optimal parameter estimation.

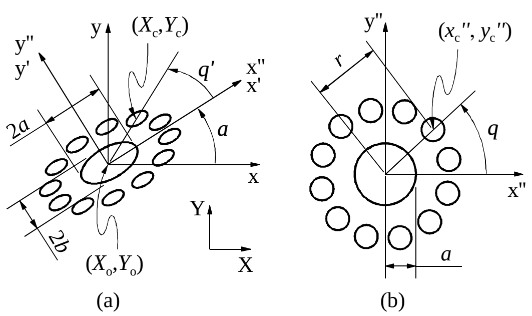


Fig. 5 Reconstruction of the circular coded target: (a) Definition of the coordinate systems by using the estimated 5 ellipse parameters (X_o, Y_o, a, b and a) of the point mark; (b) Rearranged coding points around the point mark. A valid coding point must find itself in a ring shaped zone around the point mark (see also fig. 3c), and reversibly, a valid point mark must have a valid arrangement of the coding points around it (see also fig. 3d-3e).

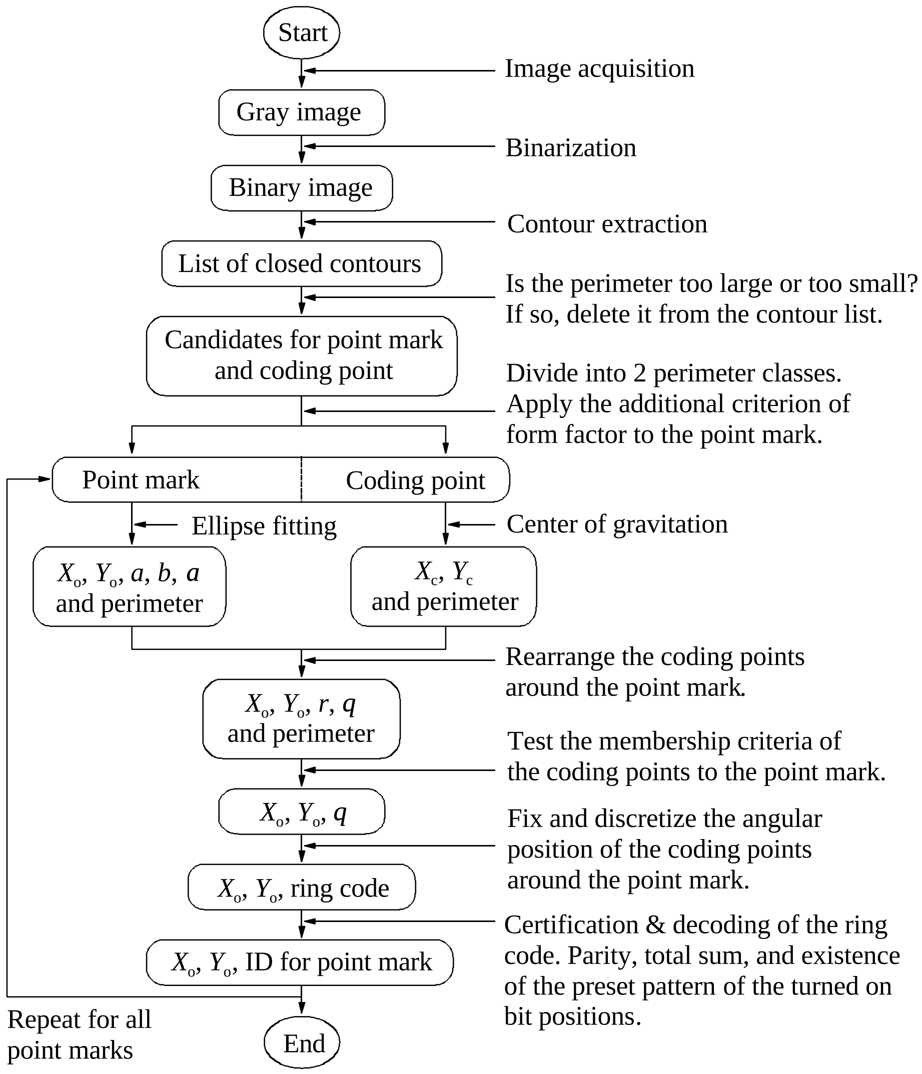


Fig. 6 Work flow of the image processing for the circular coded target.

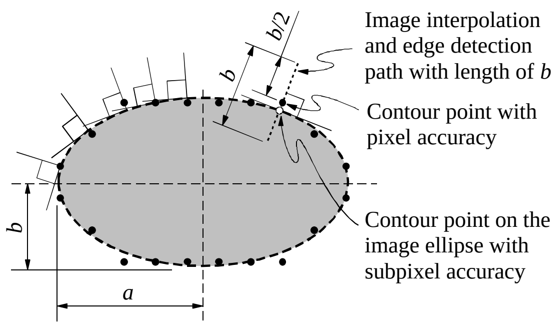


Fig. 7 Forced image interpolation and edge detection along the orthogonal path to the image ellipse. The ellipse contour points with pixel accuracy are refined to a subpixel accuracy. As a result, the succeeding ellipse fitting is more reliable and accurate than the preceding one from the pixel accurate contour points. The length constraint on the image interpolation path keeps the edge detection from straying away in noised image.

Additionally, the *forced orthogonal edge detection* is applied to the contour of the point mark by using the ellipse parameters from a preceding ellipse fitting with pixel accurate contour points (fig. 7). As a result, a robust and meaningful edge detection is also made possible in a very noised image, e.g. image of coded targets with superimposed random pattern. The succeeding ellipse fitting is more reliable and accurate than the preceding one from the pixel accurate contour points.

4 Applications

In general, in order to estimate the parameters of a system, some observations must be made by all system components, whose parameters are essentially involved in the functionality of the system. Given the system model, the model parameters can be estimated through an analysis of the observations.

In the case of stereo or multi-imaging vision systems, several widely accepted system models (camera model) and system parameter estimation (camera calibration) algorithms are already available. What we have yet to do is determine the homologous image point coordinates for some given object points, and this task can be taken over by the circular coded target and its image processing (see fig. 8a, a typical object points field for camera calibration, and fig. 8b, result of the image points measurement and identification).

As a slightly unusual application of the circular coded target, the calibration problem of the programmable LCD stripe projector [14] is considered. With various stripe projection methods, e.g. Coded Light Approach (CLA), phase-shift method and Moiré method, the projector needs to be precalibrated, since the projector parameters are directly involved in the object point determination. If we like to make use of the camera model and calibration algorithm also for the projector, the projector must image the object points field, despite it having no sensing ability. Consequently, we need a special operational method, the *virtual imaging* [15]. A regular grid pattern will be projected onto the object surface, and each projected quadrangle on the object surface can be regarded as the projection of a single virtual pixel of the projector image. Thus, if we locate an object point within the projected grid pattern, it may be said that the projector has imaged the object point (virtual imaging). To make the overall virtual imaging procedures easier, we use the circular coded target as the object point, and vertically/horizontally programmable LCD stripe projector and CLA for the registration of the virtual pixel of the projector (fig. 8).

A more difficult but very successful industrial application of the circular coded target is camera calibration for the *random pattern method*. The hardware setup of the measurement system is comprised of two high-resolution CCD cameras and a random pattern projector. The projector distinctly marks the object surface, and the two cameras simultaneously capture the patterned object surface, hence providing a stereoscopic view of the scene [11]. For the purpose of surface reconstruction through image correlation, the camera parameters at the moment of the stereoscopic imaging should be estimated. This means both the object targets for camera calibration and the patterned object surface for image correlation are imaged at the same time in each image (fig. 9a). To locate the target areas in the textured image, we have searched for the circular background plate (fig. 9b-9c). In the image processing, the constraints on

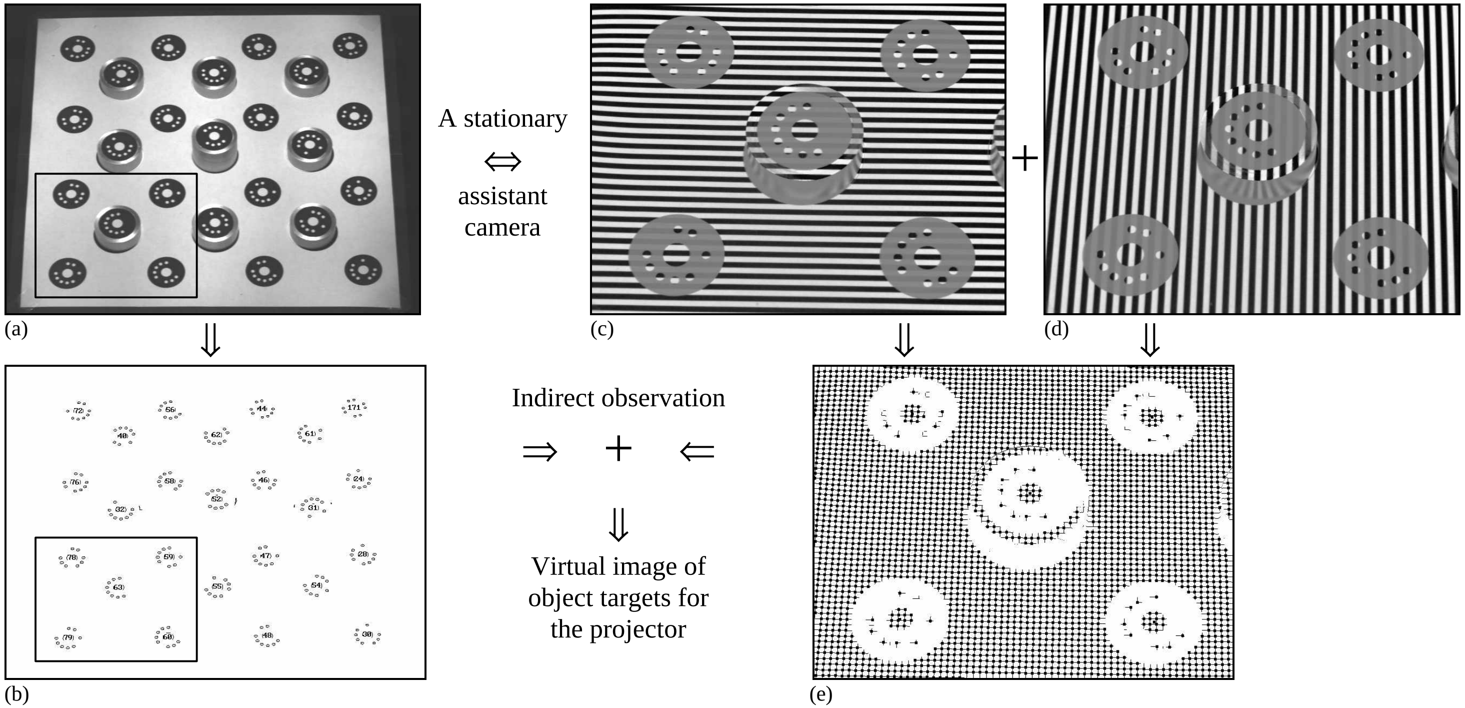


Fig. 8 Virtual imaging for vertically/horizontally programmable stripe projector: (a) Camera image of the object points field with circular coded targets; (b) Positioned and identified targets in the camera image plane; (c) Horizontal and; (d) Vertical projection of stripe patterns, where each stripe is registered through the Coded Light Approach (CLA); (e) As a curved grid pattern in the camera image plane mapped coordinate system of the projector virtual image. By means of the virtual imaging, a projector can indirectly observe the object points in collaboration with a stationary assistant camera. In the camera image plane, the object target centers and the coordinate system of the projector virtual image are mapped and superimposed together, where each quadrangle of the grid pattern in fig. 8e is the projection of a single virtual pixel of the projector and uniquely registered by CLA. Thus, if we can locate the object target centers in the grid pattern, the projector has indirectly imaged the object target centers. The subpixel accurate determination of the target center in the projector virtual image plane can be achieved through an interpolation between the stripe edge lines or through the combination of the CLA with the phase-shift method. The stationary camera needs not necessarily to have been or to be calibrated.

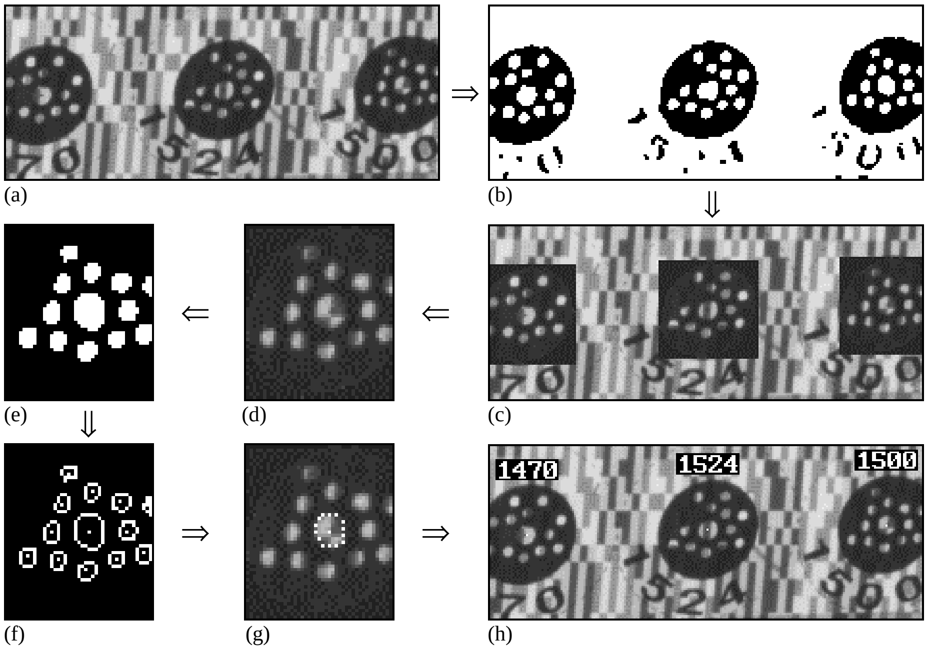


Fig. 9 Image processing of the circular coded target with superimposed random pattern: (a) Gray image (225×90 pixel) of coded targets with superimposed random pattern; (b) Optimal thresholding concerning the size and form factor of the target background plate; (c) Masked image areas for target; (d) Local gray image block; (e) Local optimal thresholding concerning the size and form factor of the point mark and the coding points, and their separation; (f) Contours of the point mark and the coding points; (g) Result of the forced orthogonal edge detection, and the estimated center of the point mark; (h) Identified and positioned target center.

target geometry as described in section 2 and 3 play an important role and guarantee a reliable object detection and identification (fig. 9d-9h). The forced edge detection enables the point mark contours to be recovered with subpixel accuracy even in the textured image (fig. 9g).

5 Discussion and conclusion

Alongside the accuracy and stability of measurement results, automation of measurement procedures is indispensable for the future industrial application of optical 3D-measurement techniques. In this paper, we have presented a new circular coded target, its image processing and application to some optical 3D-measurement methods. The special geometric construction of the target and the proper image processing make possible an accurate and reliable image point measurement and identification. The programmable arrangement of the coding points provides the adaptability of the target for all possible measuring tasks occurring in practice. The circular coded target is successfully integrated in a commercial digital photogrammetric system for surface reconstruction [16], and furthermore, we expect a general acceptance of the target with industrial applications with regard to accuracy, reliability and the automation of the measuring task.

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