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# Elimination of Un-uniformed Image Distortion Using LCD

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***Abstract***: An image calibration method involving the use of a liquid crystal display (LCD) placed in the observation medium is presented. The calibration is important for these image-based measurement techniques such as particle image velocimetry (PIV) since it influences the accuracy of measurements. One important task in calibration is to eliminate distortions, especially for images in water. In PIV, distortions have to be eliminated on every change of the target since the distortion caused by refraction varies depending on the shape of the water tank. In this paper, the proposed method is demonstrated to correctly eliminate distortion due the refraction effects of the tank and water. The method is based on the construction of a calibration table using patterns of dots displayed on the LCD in the tank, and provides excellent measurement accuracy.

***Keywords***: Calibration, Distortion, Measurement, Image processing, PIV

## I. INTRODUCTION

Calibration is important task to extract the accurate quantitative data from captured images in computer vision. This task requires estimating the relationship between the camera image and the scene prior to performing a measurement. Moreover, the calibration procedure must eliminate any distortion in the captured image.

Distortions can originate from either the characteristics of the camera lens or from the refraction of light. The distortion caused by the lens is isotropic and can be corrected relatively easily by methods such as that of Tsai [1]. Radial distortion caused by lens characteristics has also been investigated in a number of studies [2][3]. However, eliminating distortions due to refractions in the scene requires complex procedures, such as tracing the optical path by accounting for refractive index variations [4]. Due to the difficulty of such procedures, we proposed simple and useful method to eliminate the distortion caused by reflection in water, in this paper. The need for distortion correction is particularly important in particle image velocimetry (PIV) for water flow, which is a non-contact, image-based measurement technique that allows the instantaneous velocity field of flow to be determined from the translational displacement of tracer particles. In PIV of water systems, image distortion due to refraction, which is related to the shape of the water tank, must be eliminated in order to obtain quantitative measurement results.

In this study, a novel calibration technique based on the use of a liquid crystal display (LCD) [5] is applied to eliminating distortions. In this method, a waterproof LCD is placed in the water volume targeted for measurement, and a known dot pattern is displayed to allow construction of a calibration table. The experimental results demonstrate the feasibility of the proposed method for eliminating image distortion due to refraction effects.

## II. LCD-BASED CALIBRATION METHOD

Figure 1 shows a schematic diagram of the proposed calibration system. The LCD is set in the scene, and a pattern of dots is displayed. The LCD plane is set accurately on the laser plane used for PIV or slit-ray projection method, and the scene image is acquired using a complementary metal oxide semiconductor (CMOS) or charge-coupled device (CCD) camera. The dots are programmed to blink on and off according to a predefined time series, synchronized with the camera timing. An example of the encoded 4-bit dot pattern is shown in Table 1. A total of 15 patterns are possible with 4-bit encoding, and 1023 patterns can be defined with 10 bits. The dots in the acquired images are labeled according to the pattern number, and cross-referenced to the predefined dot coordinates. This decoding is performed by processing consecutive images. The world coordinates in the scene and the corresponding image coordinates of the dots are then tabulated. Conversion functions for each local area in the image are determined, and a final conversion table for the entire image is constructed. The mathematical details of the conversion functions are given in the next section. The constructed calibration table is used to convert positions from the camera image into world coordinates. Table 2 shows the calibration table, which is used as a look-up table (LUT). This calibration method is very effective for defining conversion from a distorted image to undistorted world coordinates.

There are two major benefits of using an LCD for calibration. First, thousands of reference marks (dots on the LCD) can be recognized very quickly. The time required to capture 11 images is approximately 350 ms, and even with processing for decoding of the dot patterns, the total time is less than 1 s. Second, the number, size, and display interval of reference marks can be easily changed according to the measurement environment.

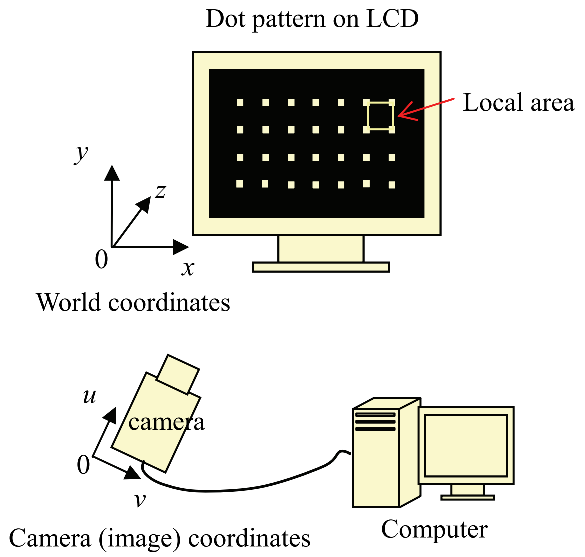


Fig.1 Schematic diagram of the calibration

Table 1. The encoded dot pattern for 4 bits

(1: On, 0: Off)

| | $T_0$ | $T_1$ | $T_2$ | $T_3$ | Number |
|---|---|---|---|---|---|
| Dot 1 | 0 | 0 | 0 | 1 | $(1)_{10}$ |
| Dot 2 | 0 | 0 | 1 | 0 | $(2)_{10}$ |
| : | : | : | : | : | : |
| Dot 15 | 1 | 1 | 1 | 1 | $(15)_{10}$ |

Table 2. Calibration table

| Image coordinates (Pixel) | | World coordinates (Actual scale) | |
|---|---|---|---|
| $u_1$ | $v_1$ | $x_1$ | $y_1$ |
| $u_2$ | $v_2$ | $x_2$ | $y_2$ |
| : | : | : | : |
| $u_n$ | $v_n$ | $x_n$ | $y_n$ |

## III. LOCAL PROJECTION MATRIX

In the pinhole camera model, the relationship between camera coordinates ($u$,$v$) and world coordinates ($x$,$y$,$z$) (see Fig. 1) is given by

$$\lambda[u \quad v \quad 1]^T = P[x \quad y \quad z \quad 1]^T \tag{1}$$

where λ is a coefficient and $P$ is the perspective projection matrix within intrinsic and extrinsic camera parameters [6]. Elements of the projection matrix are often simply referred to as camera parameters. With $z = 0$ for a two-dimensional LCD plane, eq. (1) can be rewritten as

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{2}$$

where $p_{11}$ to $p_{32}$ are elements of the projection matrix. Solving this equation to eliminate λ then affords the following relationships.

$$\begin{cases} p_{11}x + p_{12}y + p_{13} - p_{31}ux - p_{32}uy = u \\ p_{21}x + p_{22}y + p_{23} - p_{31}vx - p_{32}vy = v \end{cases} \tag{3}$$

Equations (3) consist of one set of world coordinates and the image coordinates with reference marks, comprising a total of eight unknown variables. Therefore, eight equations, or four reference marks, are required to solve the projection matrix. This process yields the following set of simultaneous equations.

$$\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -u_1x_1 & -u_1y_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -v_1x_1 & -v_1y_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_4 & y_4 & 1 & 0 & 0 & 0 & -u_4x_4 & -u_4y_4 \\ 0 & 0 & 0 & x_4 & y_4 & 1 & -v_{i4}x_4 & -v_4y_4 \end{bmatrix} \begin{bmatrix} p_{11} \\ p_{12} \\ \vdots \\ p_{31} \\ p_{32} \end{bmatrix} = \begin{bmatrix} u_1 \\ v_1 \\ \vdots \\ u_4 \\ v_4 \end{bmatrix} \tag{4}$$

Note that eq. (4) is linear, whereas the distortion due to the refraction of light is a nonlinear phenomenon. Therefore, as eq. (4) cannot be applied directly, it is assumed that the image can be divided up into a large number of sufficiently small local areas exhibiting linear behavior that can be modeled by eq. (4). The local areas are defined as each area enclosed by four reference marks, as shown in Fig. 1. The projection matrix for each local area is then determined by eq. (4) and denoted as the local projection matrix. Conversion from the image coordinates to the world coordinates is then executed for all image pixels using eq. (2) and the local projection matrixes.

## IV. EXPERIMENT

An experiment was performed to evaluate the performance of the proposed calibration system as shown in Fig. 2. The waterproof LCD was placed in a tank half-filled with water. The LCD displayed the dot pattern for calibration, and a checkered-flag pattern. A CMOS camera (640×480 pixel) was used as the capture device. To demonstrate the feasibility of this method, a low-distortion lens was used, and two shapes of water tank were tested: a cube and a cylinder. After calibration, the checkered flag pattern is measured using the constructed calibration table as an LUT, and the accuracy of measurement is evaluated.

### 1. Case 1: Cubic water tank

Figure 3 shows the captured and corrected images for the cubic water tank with flat plane shown in Fig. 2. In Fig. 3(a), the flag pattern has been distorted in water; it should be the same size and shape with that in air. Although some distortion remains near the water surface, the corrected pattern in water conforms to that expected in air (Fig. 3(b)). This result indicates that the image distortion caused by water has been corrected for appropriately.

### 2. Case 2: Cylindrical water tank

Figure 4 shows the cylindrical water tank used in the second test. The diameter of the tank tapers from the top to the base, and the distortion caused by the tank and water is expected to be more severe than in case 1. Figure 5 shows the captured and corrected images. The distortion in this case is much more severe than for the cubic tank. Whereas no distortion occurs in the air region in the cubic tank, distortion is apparent in both air and water in the cylindrical tank (Fig. 5(a)). This can also be seen in the captured image of the dot pattern as shown in Fig. 6. Unevenness in the glass forming the cylindrical tank is indicated by the small-scale displacements of the dots. The distortion transformation is thus more complicated than in case 1. After correction, most of the flag pattern was well reconstructed, as in case 1, although some distortion remains at the water surface (Fig. 5(b)). These results indicate that distortion in both water and air can be corrected simultaneously, and that the proposed method provides robust correction even for complex shapes and complicated transformations.

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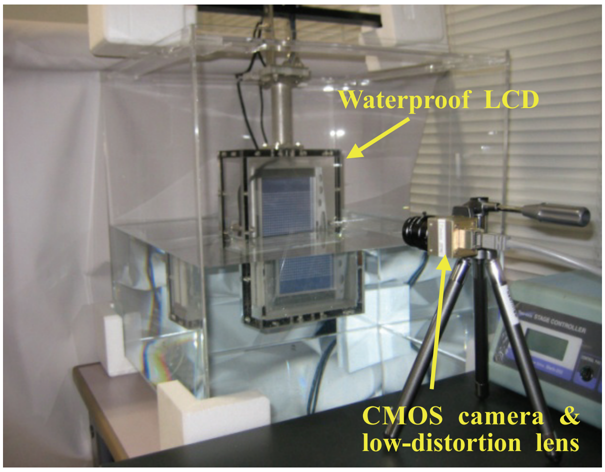
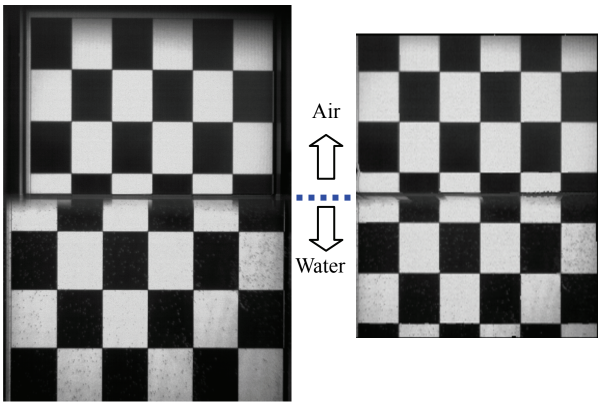



Fig. 2 Calibration in a cubic tank




(a) (b)

Fig. 3 (a) Captured image and (b) corrected image of flag pattern acquired in a cubic tank

**3. Accuracy of measurements**

The measurement accuracy was evaluated by measuring the length of a side of the flag pattern in case 2. The original captured image and constructed calibration table were used to calculate the final measurements. The world coordinates of two neighboring vertices were found from the calibration table and used to determine the actual length by computing the distance between two points. The accuracy of measurements was thus found to be 0.17 mm in the water region and 0.21 mm in the air region. These values are equivalent to 1.4 % and 1.8% of total length, respectively. The measurement accuracies in both water and air are thus approximately the same.

## V. CONCLUSION

A new LCD-based calibration technique was demonstrated to correctly eliminate image distortion due to external refractions in both water and air simultaneously. Excellent correction results were obtained even for complex tank shapes, and the measurement accuracy was shown to be adequate. The proposed technique is considered highly effective for PIV in water, and is potentially applicable to the shape measurement of objects in water using the slit-ray projection method. This technique was applied in the present study for two-dimensional measurements. However, if the position of the laser illumination plane and the camera can be fixed and the object moved, it will also be possible to apply this technique to three-dimensional measurements.

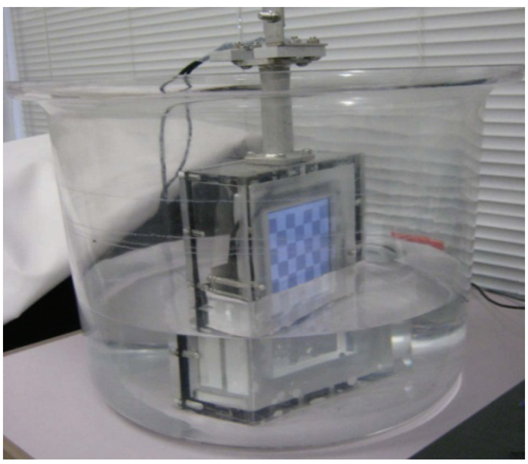
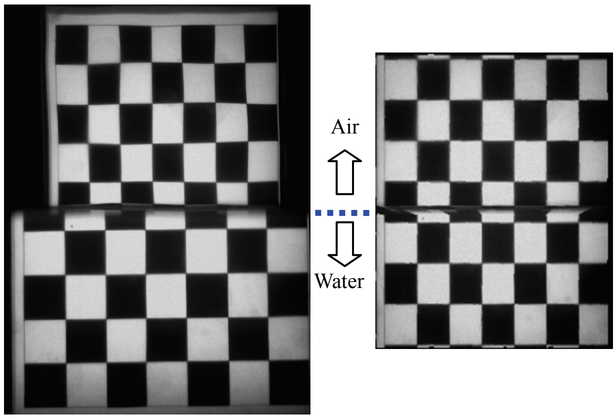
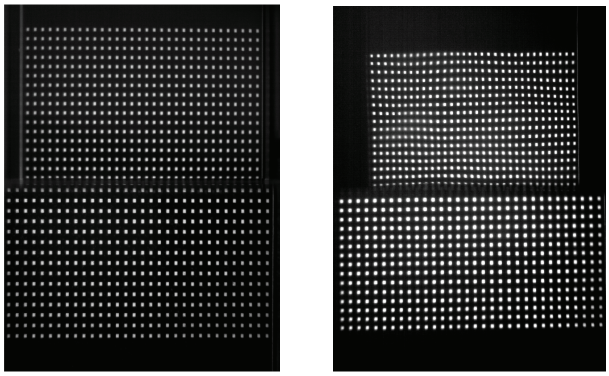


Fig. 4 Calibration in a cylindrical tank




(a) (b)

Fig. 5 (a) Captured image and (b) corrected image of flag pattern acquired in a cylindrical tank



(a) Case 1 (b) Case 2

Fig. 6 Captured images of dots pattern in (a) the cubic tank and (b) the cylindrical tank

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