Real-Time 2D Displacement Measurement of Four Points LED Markers with One Camera Image

Yasushi NIITSU¹, Takaaki IIZUKA² and Kenta YASUOKA³

¹ School of Information Environment, Tokyo Denki University, Chiba 270-1382, Japan
² Graduate School of Advanced Sci. and Tech., Tokyo Denki University, Tokyo 120-8551, Japan
³ Graduate School of Information Environment, Tokyo Denki University, Chiba 270-1382, Japan

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Abstract
Two dimensional displacement of the lighting marker on a plane can be measured with one camera image. However, the measuring process needs the complex calibration of the coordinate system and of the camera states. The developed 2D displacement measuring method can detect the displacements of several four-point LED (Light Emitting Diode) markers, without the complex calibrations. With our method, the camera parameters, which characterize the camera status, can automatically be determined with four positions of the lighting LED on the local coordinate system, for each four-point LED marker. The high-resolution and high-speed camera was used for the development of software and for the displacement measurement. The resolution power of the CCD was 1024x768 pixels for each monochromatic 8 bits resolution, and the sampling interval was 100 times per second. It was confirmed that our method could measure the displacement with enough resolution power, for the purpose of the displacement measurement by the large scale extensometers.

Key words
Displacement Measurement, 2D Measurement, Real-time Measurement, Image Processing, LED Marker

1. Introduction
The measurement of positions, displacement and strain with camera image is useful for the evaluation of the structures, because of its non-destructive and non-contacting technique [1-4]. The authors developed the 3D-position measurement system with several high-speed cameras, and used it for the 3D-measurement of structures submitted to vibration testing [5, 6]. The 2D-measurement, by detecting the light-markers, was also developed to detect the strain distribution on the wooden board, which suffered the shear force of the testing [7, 8].

For the 3D measurement, the camera parameters, which connect true 3D space and camera coordinates, should be precisely determined before measurement. For the determination of the camera parameters, the relation between the 3D coordinates in true space, and 2D coordinates on the camera screen, was required at more than six points. However, if the movement of the target is limited to the plane, the camera parameters can be determined from the position information of only four points. In this paper, the authors introduce the special marker with four LED lights to realize automatic calibration of the camera parameters for the 2D displacement measurement, by image processing. The experiments for the evaluation of the accuracy of the measurement were performed in the laboratory. From our experimental results, the usefulness of this measurement method was confirmed, for this type of testing.

2. Principle of Measurement
If the target points move in a plane, the position of the target points are determined by adopting the oblique/perspective coordinate system on the camera screen as shown in Fig. 1. In general, the relation between the camera screen coordinates (X, Y) and the true 3D space coordinates (x, y, z) is given by the following equations:

\[
\begin{align*}
C_{11}x + C_{12}y + C_{13}z + C_{14}yX - C_{12}yY &= X \\
C_{21}x + C_{22}y + C_{23}z + C_{24}yX - C_{22}yY &= Y
\end{align*}
\]

where, \(C_{ij} (i=1,2,3; j=1,2,3,4)\) are eleven real numbers representing the linear camera parameters.

2.1 Determination of camera parameters
There are eleven \(C_{ij}\) real numbers representing camera parameters. However, if the target point only moves in a x-y plane as shown in Fig.1, then the z-coordinate is zero and the Eqs.(1) are rewritten as follows:

\[
\begin{align*}
C_{11}x + C_{12}y + C_{14} - C_{12}yX &= X \\
C_{21}x + C_{22}y + C_{24} - C_{22}yY &= Y
\end{align*}
\]

The equations (2) have eight \(C_{ij}\) parameters and they can be solved with four sets of relations of \((x,y,0)\) and \((x,Y)\). The authors suggest the target marker, which has four points LED (Light Emitting Diode) markers, without the complex calibrations. With our method, the camera parameters can automatically be obtained from the Eq.(3) from the first camera image of the markers.

\[
\begin{align*}
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & a & 1 & 1 & 0 & 0 & 0 & 0 & aX_f^m & 0 \\
0 & 0 & 0 & 0 & 0 & a & 1 & 1 & 0 & 0 & 0 & aX_f^m & 0 \\
0 & 0 & 0 & 0 & 0 & a & 1 & 1 & 0 & 0 & 0 & aX_f^m & 0 \\
0 & 0 & 0 & 0 & 0 & b & 1 & 0 & 0 & 0 & 0 & bY_f^m & 0 \\
0 & 0 & 0 & 0 & 0 & b & 1 & 0 & 0 & 0 & 0 & bY_f^m & 0 \\
0 & 0 & 0 & 0 & 0 & b & 1 & 0 & 0 & 0 & 0 & bY_f^m & 0 \\
0 & 0 & 0 & 0 & 0 & b & 1 & 0 & 0 & 0 & 0 & bY_f^m & 0 \\
\end{bmatrix}
\begin{bmatrix}
C_{11}^m \\
C_{12}^m \\
C_{13}^m \\
C_{14}^m \\
C_{21}^m \\
C_{22}^m \\
C_{23}^m \\
C_{24}^m
\end{bmatrix}
= \begin{bmatrix}
X_1^m \\
y_1^m \\
X_2^m \\
y_2^m \\
X_3^m \\
y_3^m \\
X_4^m \\
y_4^m
\end{bmatrix}
\]

(3)
where, \((X_i^m, Y_i^m)\) \((i = 1 – 4,\) and \(m\) representing the marker’s number) denote the positions of the four LED on the camera screen coordinates as shown in Fig. 3. It is assumed that the target moves on the \((x, y)\) plane two-dimensionally. The displacement \((x, y)^m\) of each marker is calculated by Eqs.(2) substituting \(C_{ijm}\) to \(C_{ij}\). The process of calculation of the displacement only needs the size of the marker’s diamond \((2a, 2b)\).

2.2 Calculation process of the marker displacement

The displacement of the marker \((x, y)\) is calculated by Eqs.(2) and (3). The camera parameter \(C_{ijm}\) must be obtained before the displacement measurement, as an initialization process.

2.2.1 Initialization process

Before starting the measurement, the camera parameters must be determined for each four-points marker. The following steps must be carried out as an initialization processes:

1) Input the size of marker’s diamond \((2a, 2b)\)
2) Capture the image at the zero displacement state.
3) Search four-point diamonds on image, and automatically set their local coordinate.
4) Calculate \(C_{ijm}\) for each four-points marker with Eq.(3).

2.2.2 Calculation process of displacement

After starting the measurement, the following processes must be performed for each frame. In our measurement, the frame speed (sampling speed) is 100 frames per second.

1) Capture the image.
2) Search four-point diamonds near the position of the four-points markers on the image.
3) Calculate the center of the four-points markers on the image, and obtain their 2D positions using Eqs.(2). The displacement of the four-points marker corresponds to the average value of movements of the four lights.

3. Equipment and Measuring Method

3.1 Equipment

Two kinds of four-points markers and one high-speed camera are used in the experiments. Figure 4 shows the markers and a camera. The sizes of the four-points markers are \((132.1, 91.4)\)mm and \((69.5, 42.5)\)mm, as \((2a, 2b)\) in Fig.2. The size of the digital image is 1024 x 768 pixels and the resolution for each pixel is 8 bits gray scale. The focus distance of the lens is 25mm. The real-time tracking and measurement of the displacement of several markers are performed by a Core i5, 3.2GHz computer. The sampling interval is 0.01 second. The computer has a 16bits 2channel D/A converter and two displacements can be outputted as voltages in the -10V to 10V range.

3.2 Detection of the four-points marker

The LED points appear as the set of the high bright pixels of diameter \(d\) \((d\) is from 4 to 10 pixels) on the image, therefore the position of the LED points can be detected as the center of the set of those pixels \([6],[7]\). The positions of the four-points markers are detected with the structure of the diamond shape. As two diagonals divide each other in half for the diamond, the four-points markers can be automatically found with the condition of the diamond shape. The automatic search of the markers must be carried out at the initialization process. When the miss setting of the search occurs, the collection and the modification can be made by manual labor.

**Fig. 1** Perspective coordinates on a camera screen

**Fig. 2** Two kinds of four points LED markers used in the experiment

**Fig. 3** Local coordinates of \(m\)-th four-points marker

**Fig. 4** Photographs of two kinds of four-points markers (small and large) and a high-speed camera
3.3 Real time processing
To realize the real-time measurement faster than 0.01 second for each frame, the search of each LED point of the marker follows the partial image of its neighborhood. The image data, that should be handled, becomes less than 10% of full image by searching for only a partial neighborhood image.

3.4 Measuring method
The displacement can be measured from any view position of the camera, theoretically. Each four-points marker has the individual local (x, y) coordinates, therefore it is possible to measure the displacements of several four-points markers at the same time. Figures 5 (a) and (b) show the conditions of two kinds of experiments. Experiment A, as shown in Figs.(a), is to check the independence of the camera view point. Large four-points marker is moved three different direction with a linear actuator. The accuracy of the linear actuator is better than 0.01mm. Experiment B, as shown in Figs.(b), is to examine the accuracy and the resolution power of the measurement. Three small four-points markers are attached on the board and moved with the linear actuator.

4. Experimental Results
In order to check the possibility of the displacement measurement with the camera parameter, the four-points marker was put on the linear actuator and moved three different directions, at an angle of 0, -45 and 45 degree, as shown in Figs.5 (a). The photograph of Fig.5 (a2) shows the camera image of the condition of 45 degree direction.

In this experiment, the large four-points marker was used. Figure 6 shows the results of this experiment. The measured results of three different directional movements of the markers are close each other, and the differences between the measured displacement and the actuator’s movement are less than 5% at 200 mm actuator’s movement. Therefore our method is independent of the installation position of the camera and the markers, thus, it is easy to set the camera as well as the markers, at convenient locations.

The second experiment is to examine the accuracy of the measurement and possibility of the two directional displacement measurements. Three small four-points markers were fixed on the board on the linear actuator. Figure 7 shows the photograph just after the automatic initialization. The size of the marker (2a, 2b), in Fig.2 on the image, is (90.11, 54.85) pixels. The local coordinates and the camera parameters were determined at this state. No.1 marker was inclined -30 degree from the horizontal direction. No.2 marker was installed so that the longer diagonal line to be the vertical direction. No.3 marker was installed so that the longer diagonal line to be the horizontal direction. The directions of the local coordinates...
are shown in Fig. 5 (b2). The movement of the linear actuator starts from the 0mm position and the steps are as followings:

0mm --> 100mm --> 100.5mm --> 101.5mm --> 103.5mm --> 107.5mm --> 103.5mm --> 101.5mm --> 100.5mm --> 100mm --> 0mm.

The step differences are 100, 0.5, 1.0, 2.0, 4.0, -4.0, -2.0, -1.0, -0.5 and -100 mm.

Figure 8 shows the results of this step moving experiment. The step of 0.5 mm can be clearly obtained. Since No.1 marker was inclined 30 degrees, $x_1$ and $y_1$ displacements were smaller than the actuator’s movement. Figure 9 shows the comparison of the $x_3$ (the x-displacement of No.3 marker) with the movement of the actuator. About 1.5 mm difference between the measured and ideal displacement can be observed. Figure 10 shows the displacement of No.2 and No.3 markers from the first step position. The horizontal axis means the actuator’s displacement. The maximum difference between the measured results and the actuator displacements is 0.29 mm at 7.5 mm displacement. It is considered that the cause of this difference is due to the errors in the measurement of four light positions in mm. The noise of the measurement in a stop state was less than 0.00012 mm standard deviation and it was very small.

The experiment, in which the actuator moves from 0 mm to 300 mm, with 3.0 mm/sec velocity, was performed, and actuator’s displacement was measured in the same conditions as in the Fig. 5 (b2). The results were shown in Fig. 11. The values of $y_2$ (the y-displacement of No.2 marker), $x_3$ (the x-displacement of No.3 marker) and $\sqrt{x_1^2+y_1^2}$ (absolute displacement of the No.1 marker) can be expected to coincide with the actuator’s displacement. However, the difference between the measured results and the actuator’s movement can be observed at 300mm position as a value of about 24 mm in the x-displacement of the No.3 marker. This difference corresponds to an error of 8%. The error in the long distance movement may be caused by the distortion of the lens and the error of the measurement of the four light positions.

5. Conclusions

The authors introduce the diamond shape marker with four LED light to realize automatic calibration of the camera parameters for the 2D displacement measurement by image
processing. The experiments for the evaluation of the accuracy of the displacement measurement were performed. The measurement results were compared with the actuator movement in several displacement conditions. From the experimental results, the usefulness of this measurement method was confirmed. The 2D displacement \((x, y)\) can be obtained easily by Eqs. (2). The search of the marker follows the partial image of the marker neighborhood to realize real-time processing.

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**References**


