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Contents

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Three-dimensional Quantitative Visualization from a Single Image

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Abstract: By setting a refractor at an angle to the optical axis of a closed circuit display (CCD) camera lens, the image of a measurement point recorded on the image plane is displaced by an amount that corresponds to the distance between the camera and the measurement point. When the refractor is rotated at high speed while the camera is operating, the image of the measurement point appears as an annular streak. Since the radius of the annular streak is inversely proportional to the distance between the camera and measurement point, the three-dimensional (3-D) position of the measurement point can be obtained by extracting data from the streak.

In this paper, this system is applied to measure a moving surface. To do this, multiple laser spots are projected onto the surface. The position of each laser spot reflected from the surface is measured using a circular dynamic stereo system. Moreover, this system is applied to flow measurement as a potential application and the results are described. *Copyright © 2009 IFSA.*

Keywords: Image processing, CCD camera, Refractor, Free surface, Flow measurement

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1. Introduction

The use of computer visual systems to obtain three-dimensional (3-D) data is finding applications in various fields. The automatic inference of 3-D data has been and continues to be one of the primary aims of computer vision systems. Various methods have been developed for obtaining 3-D data. One method is based on stereovision with two or more closed circuit display (CCD) cameras [1, 2] and another is based on the slit-ray projection method [3, 4]. In the stereovision method, the depth of measurement points is determined by measuring the disparity between matching pairs in frames viewed at different angles. One problem with this method is that finding matching pairs in different frames requires a considerable amount of computer processing since there are usually several candidates for the matching points. In the slit-ray projection method, the object being measured is reconstructed from many images in which the structured light (slit rays) is projected from different positions. A quantitative measurement is performed by considering the geometric configuration between the CCD camera and the structured light. In this method, the measurement object must remain stationary while the structured light is scanned over its surface. Thus, with the exception of some systems, a moving object cannot be measured by the slit-ray projection method [5–8].

In this paper, a new technique is introduced for measuring the instantaneous 3-D positions of multiple points by analyzing a single image. The principle feature of this technique is that it uses a single CCD camera with a system for shifting the image. By introducing a refractor in front of the CCD camera lens, the image of the measurement point is shifted by an amount that is a function of the distance between the CCD camera and the measurement point. When the refractor is rotated at high speed while the CCD camera is operating, the measurement points appear as annular streaks in the image since a rotational shift is imparted to the image. Since the radius of the streaks is inversely proportional to the distance of the measurement point from the camera, each annular streak contains 3-D information about the measurement point. This information can be extracted by analyzing the annular streaks. Reliable information can be obtained since this system does not require the measurement points in different frames to be matched. This method has been applied to measure tracer particles in flows and satisfactory results were obtained [9–12].

Calibration is an important task in computer vision since it influences the measurement accuracy. A suitable calibration method for our system is developed and the measurement accuracy is checked.

In this paper, the measurement of a moving surface, such as swinging water, is considered as another application of our system. This measurement is realized by utilizing the characteristics of a circular dynamic method and a multiple laser-spot projector. The results obtained demonstrate the feasibility of our method. Moreover, this system is applied to the flow measurement as a potential application and the results are described.

2. Measurement System

2.1. Circular Dynamic Stereo System

A schematic diagram of our imaging system is shown in Fig. 1 and a photograph of the system is shown in Fig. 2. By introducing a refractor in front of the CCD camera lens, the image of the measurement point is shifted with a displacement that corresponds to the distance between the CCD camera and the measurement point. That is, the displacement r in the image is inversely proportional to the distance D between the measurement point and the camera, so that D is given by:

$$D = \frac{f \cdot d}{r}, \tag{1}$$

where f is the focal length of the camera and d is the magnitude of the shift caused by the refractor. When the refractor is rotated at high speed while the CCD camera is operating, the measurement point appears as an annular streak in the image, since a rotational shift is imparted to the image. Since the radius of the streak is inversely proportional to the distance of the measurement point from the camera, each annular streak contains 3-D information on the measurement point. The location and the radius of the annular streak in the image are related to the 3-D position of the measurement point.

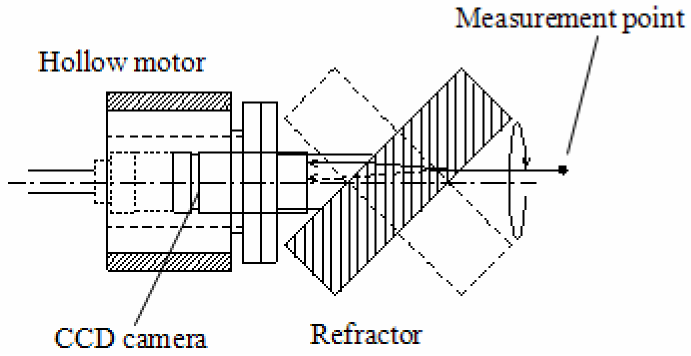


Fig. 1. System setup.

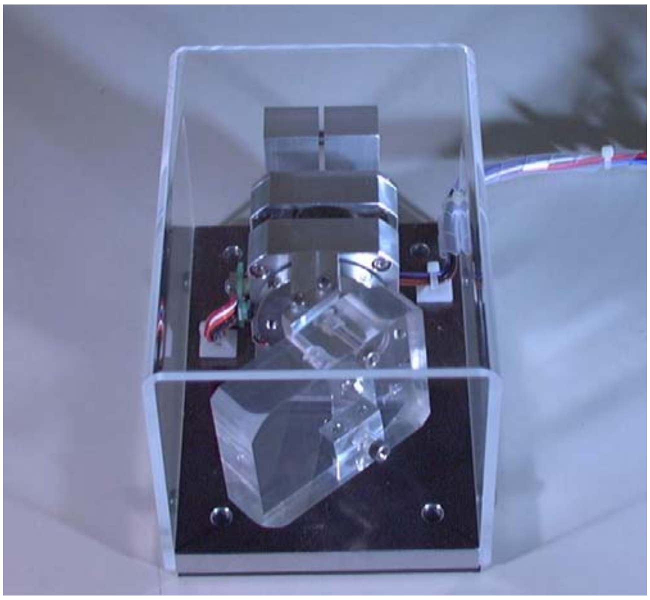


Fig. 2. Circular shifting system.

2.2. System Configuration

The setup of the 3-D measuring system is shown in Fig. 3. Multiple laser spots are projected onto the surface of the object from the location of the CCD camera. The laser spots on the surface of the object trace out annular streaks or an equiangular spiral streak (for the case when the object is moving) and the diameter of each streak corresponds to the distance from the CCD camera to the laser spot. Thus, 3-D information for multiple points is recorded in a single image. Fig. 4a shows multiple laser spots projected onto the surface of the object and Fig. 4b shows an image with circular shift obtained using our system. Small annular streaks represent laser spots on the surface of a distant object and large annular streaks represent laser spots on the surface of a near object.

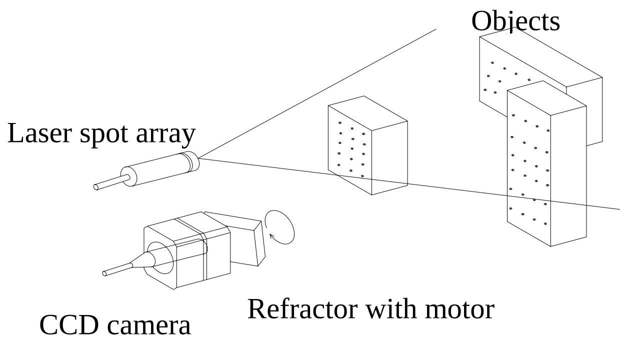
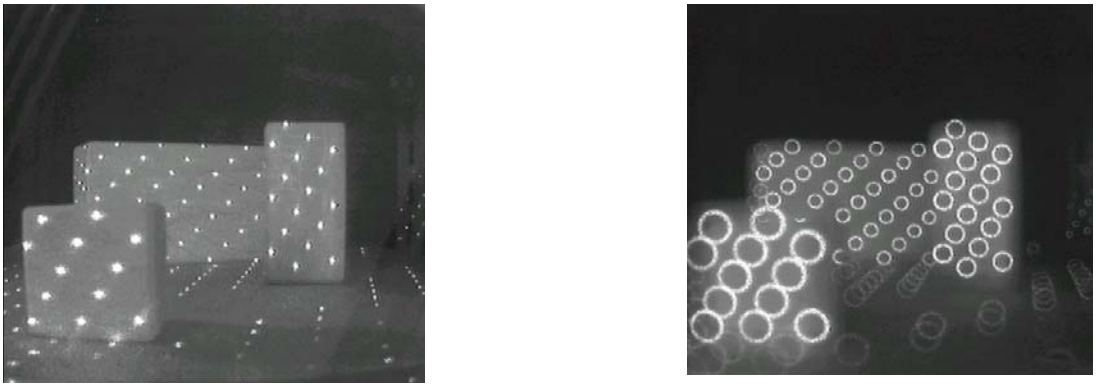


Fig. 3. Experimental setup using multiple laser spots.



(a) Multiple laser spots on the surfaces of objects.

(b) Image with a circular shift.

Fig. 4. Image obtained by circular dynamic stereo system.

3. Calibration Method

The information required from an image for 3-D measurements is the center position and the radius of each annular streak. The center (u_c, v_c) and the radius r_c of the annular streak are obtained to sub-pixel accuracy by applying the Hough transform (Fig. 5).

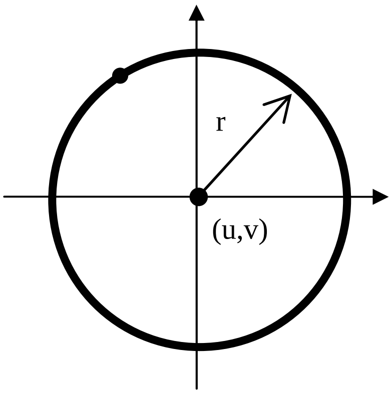


Fig. 5. Extraction of annular streaks.

The annular streak data is converted to world coordinates (x_f, y_f, z_f) that are centered on the focal point of the CCD camera and that are defined by the following transform:

$$\begin{bmatrix} x_f \\ y_f \\ z_f \end{bmatrix} = \frac{d}{r_c} \begin{bmatrix} u_c \\ v_c \\ f \end{bmatrix}, \qquad (2)$$

where d is the magnitude of the shift produced by the refractor and f is the focal length of the CCD camera.

The relationship between the camera coordinates and the world coordinates is transformed to homogeneous coordinates by setting $z=s$ in (2).

$$s\begin{bmatrix} u_c \\ v_c \\ r_c \\ 1 \end{bmatrix} = \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 0 & fd \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_f \\ y_f \\ z_f \\ 1 \end{bmatrix} \qquad (3)$$

The relationship between the 3-D points in the world coordinate system that is defined relative to the measuring bench and the corresponding camera coordinate system is defined by a perspective transformation. Let the world coordinates of the object point be X, Y, and Z and the corresponding camera coordinates be u_c, v_c and r_c. The following equation is then satisfied.

$$s\begin{bmatrix} u_c \\ v_c \\ r_c \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \qquad (4)$$

Using the least squares error method, the values of h_{ij} can be determined by sampling over five distinct non-coplanar points whose world coordinates are already known, with camera coordinates and the corresponding value of r.

The procedure for feeding the sampling pairs into a computer is as follows. The system setup for calibration is shown in Fig. 6. The world coordinate system is defined relative to the measuring bench such that the Y- and Z-axes lie on the bench and the X-axis extends perpendicularly upward from the bench. An (x, y) scale is placed on the surface of a calibration board; the calibration board can be translated using a z stage.

Multiple laser spots are projected onto the surface of the calibration board.

The annular streaks are recorded by the circular shifting system with a bandpass filter and the position (u_i, v_i) and radius (r_i) of each streak are estimated (Fig. 7).

The (x, y) scale on the calibration board is also recorded at the same position by the system with the bandpass filter removed.

The (x, y) scale is displayed on the monitor (Fig. 8).

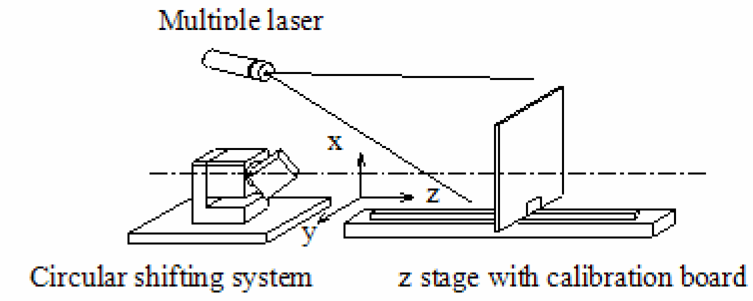


Fig. 6. Calibration setup.

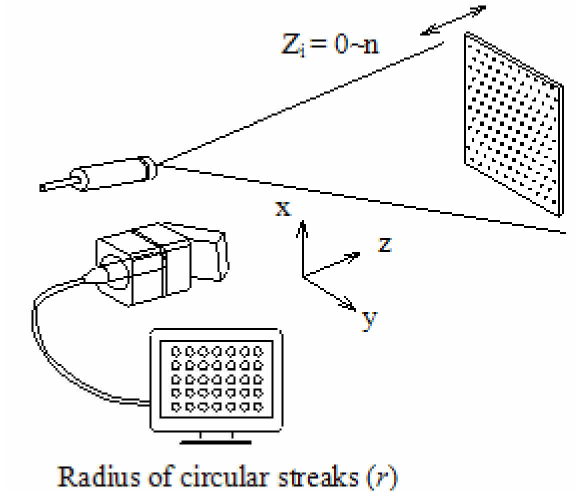


Fig. 7. Detecting annular streaks.

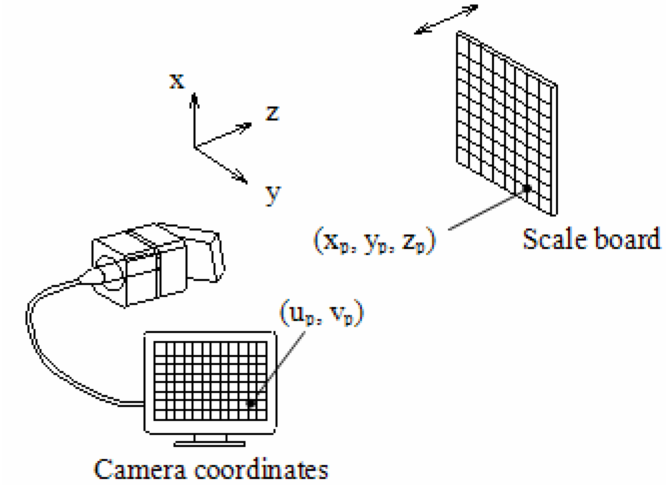


Fig. 8. Detecting pairs of coordinates.

The camera coordinates (u_p, v_p) are entered onto the computer by using the mouse to point to the x, y scale on the monitor and entering the corresponding world coordinates (x_p, y_p, z_p) using the keyboard. The value of r_p at (u_p, v_p) is determined by the radii of the surrounding annular streaks in accordance with the following equation:

$$r_p = \frac{\sum_i r_i \cdot \frac{1}{l_i^2}}{\sum_i \frac{1}{l_i^2}}, l_i^2 = (u_p - u_i)^2 + (v_p - v_i)^2, \tag{5}$$

where r_i is the radius of the annular streak enclosing $(u_p,\ _{vp})$.

The calibration board is translated in the *z* direction and other coordinate pairs are fed into the computer by repeating the above steps.

Rearranging (4) yields

$$T\eta = \chi \ , \tag{6}$$

where

$$T = \begin{bmatrix} x_1 & y_1 & z_1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -u_1x_1 & -u_1y_1 & -u_1z_1 \\ 0 & 0 & 0 & 0 & x_1 & y_1 & z_1 & 1 & 0 & 0 & 0 & 0 & -v_1x_1 & -v_1y_1 & -v_1z_1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_1 & y_1 & z_1 & 1 & -r_1x_1 & -r_1y_1 & -r_1z_1 \\ & & & & & & & : & & & & & & & \\ & & & & & & & : & & & & & & & \\ x_n & y_n & z_n & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -u_nx_n & -u_ny_n & -u_nz_n \\ 0 & 0 & 0 & 0 & x_n & y_n & z_n & 1 & 0 & 0 & 0 & 0 & -v_nx_n & -v_ny_n & -v_nz_n \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_n & y_n & z_n & 1 & -r_nx_n & -r_ny_n & -r_nz_n \end{bmatrix}$$

$$h = \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{14} \\ : \\ h_{43} \end{bmatrix}, c = \begin{bmatrix} u_1 \\ v_1 \\ r_1 \\ u_2 \\ : \\ r_n \end{bmatrix}$$

Since the coefficient matrix *T* and vector *h* in (6) are determined by the set of world coordinates and the corresponding camera coordinates of over twenty distinct points are known, the solution of (6) can be obtained as follows using the least squares error method.

$$h = (T^tT)^{-1}T^tc \tag{7}$$

After determining the matrix *h*, measurements can be performed by applying the following equation to each measurement point.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} h_{41}u - h_{11} & h_{42}u - h_{12} & h_{43}u - h_{13} \\ h_{41}v - h_{21} & h_{42}v - h_{22} & h_{43}v - h_{23} \\ h_{41}r - h_{31} & h_{42}r - h_{32} & h_{43}r - h_{33} \end{bmatrix}^{-1} \begin{bmatrix} h_{14} - u \\ h_{24} - v \\ h_{34} - r \end{bmatrix}, \tag{8}$$

where *(u, v)* is the center point and *r* is the radius of an annular streak generated by a measurement point.

4. Experiment

4.1. Evaluation of Measuring Accuracy

In order to evaluate the feasibility of our system, the following experiment was conducted. The plane board was set parallel to the image plane of the CCD camera at a known distance from the CCD camera. The measurement point was illuminated on the surface of the board by a laser spot. The laser spot traces out an annular streak by using the circular dynamic system. The image data of the circular streak was stored as an image file (resolution: 512×512) and a computer (CPU: 2.4 GHz) was used to calculate the position of the laser spot. The distance of the board from the CCD camera was varied from 50 mm to 350 mm in intervals of 10 mm. The results of this experiment are shown in Fig. 9. This graph plots the average error for the distance measurements. It has a systematic tendency in a positive direction as indicated by the curved line. The systematic error function can be obtained from these results. The final measurement results are determined by considering the systematic error function to compensate the systematic errors. Fig. 10 shows the measurement performance of our system after eliminating the systematic error.

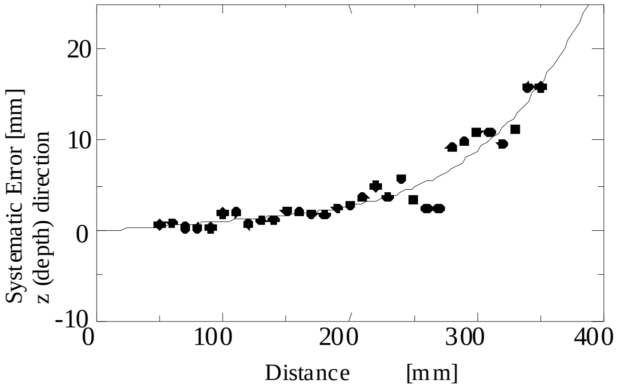
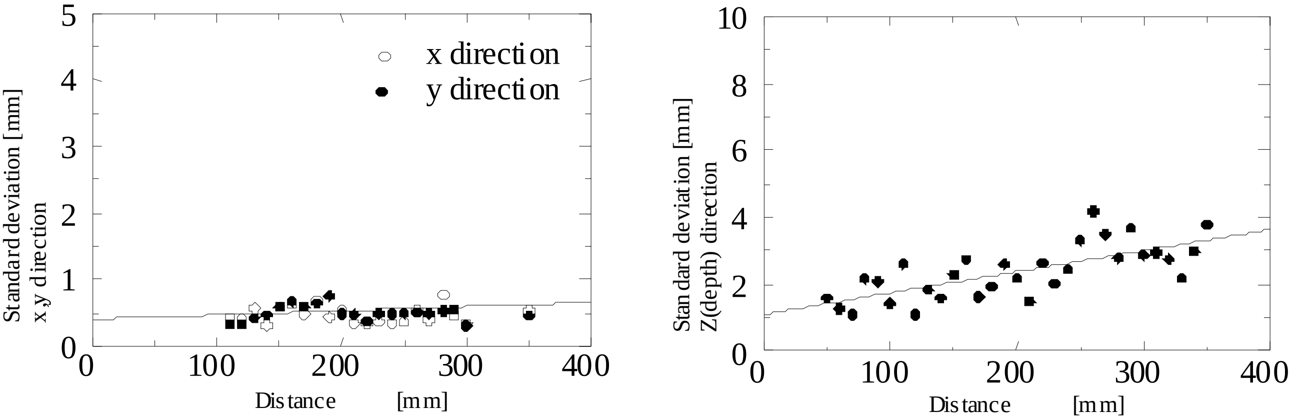


Fig. 9. Accuracy of the measurement system.



(a) (x, y) direction.

(b) z (depth) direction.

Fig. 10. Accuracy of the measurement system after eliminating the systematic error.

4.2. Surface Measurement of Water

The experimental setup is shown in Fig. 11. Aluminum powder with an average particle size of 20 μm is introduced on the water surface. This powder forms a thin film on the surface of water and moves with the movement of water. Multiple laser spots (30 mW) are projected onto the water surface and are reflected by the aluminum powder. Fig. 12a shows an image of the multiple laser spots on the water surface. Fig. 12b shows an image with a circular shift. Fig. 13 shows the reconstructed water surface in two consecutive images.

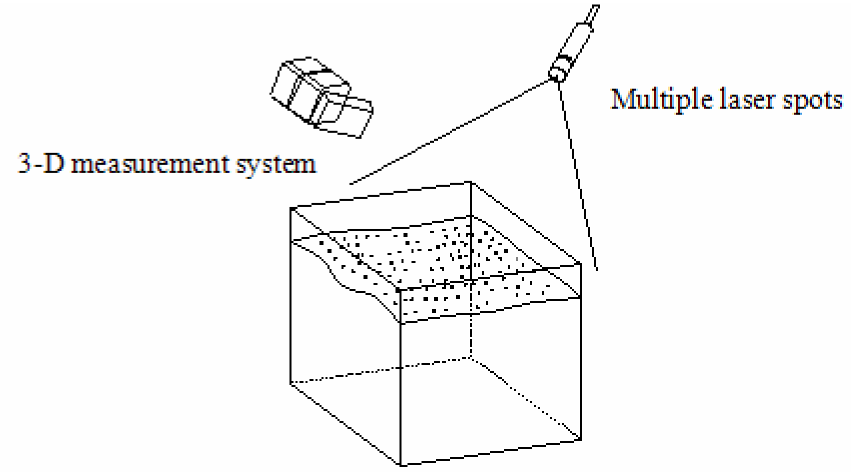
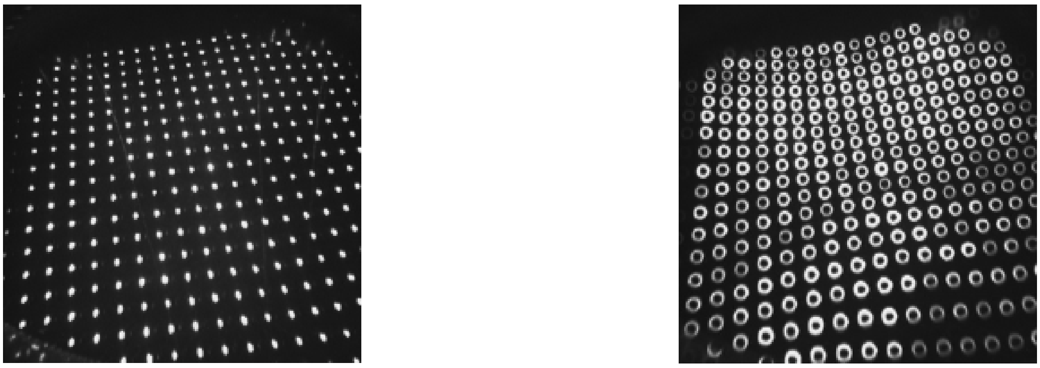


Fig. 11. Experimental setting for surface measurement.



(a) Multiple laser spots without a circular shift.

(b) Multiple laser spots with a circular shift

Fig. 12. Example of an image on the water surface.

4.3. Flow Measurement Using Tracer Particle

As an application of this system, the measurement of flow around an object was conducted. Fig. 14 shows a schematic diagram of the measurement system. As shown in this figure, the flow was measured around a wing model that is located in the test section (2 m (breadth) × 1 m (depth) × 5 m (length)) of a circulating water channel. By mixing tracer particles that were 500 μm in diameter and had a specific gravity of 1.04 with the flow, the 3-D movement of each tracer particle around the wing model was measured, and the flow around the wing model was analyzed indirectly. The experimental conditions are shown in Table 1.

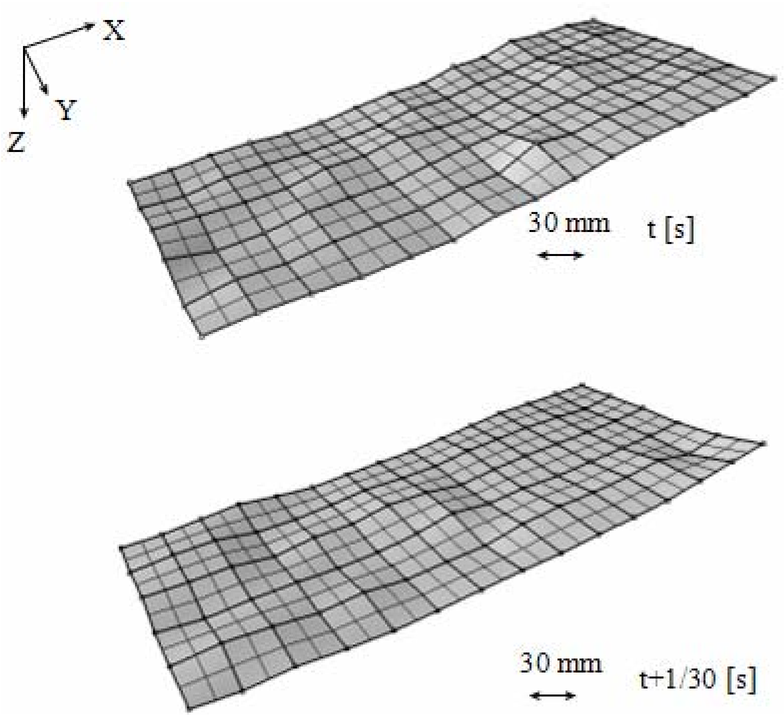


Fig. 13. Experimental results for surface measurement.

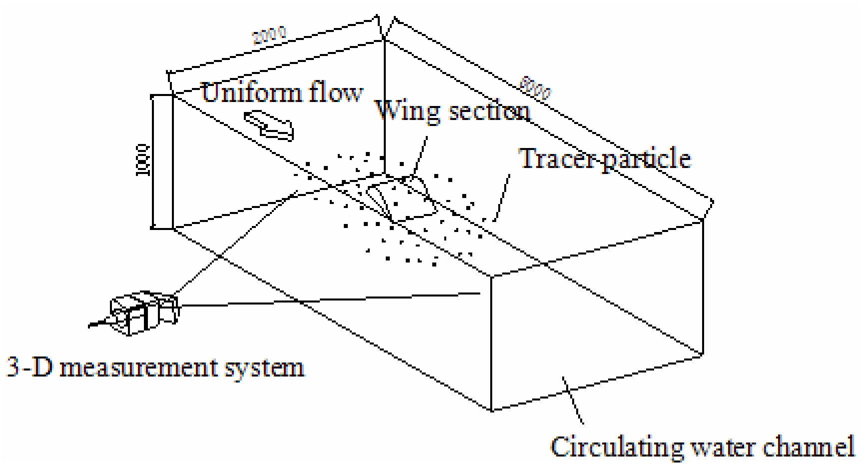
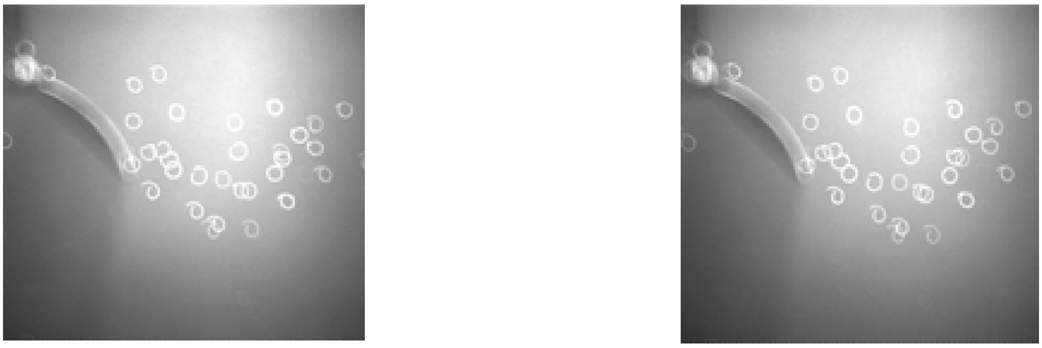


Fig. 14. Experimental setup of flow measurement using tracer particle.

Table 1. Experimental condition.

Flow velocity	**0.5 m/s**
Type of tracer particles	Polystyrene beads
Size of tracer particles	500 µm
Specific gravity of tracer particles	1.04
Interval	1/60 sec.

Fig. 15 shows images of the tracer particles obtained using this system. These images are sequential images. The tracer particle velocity is determined from the relation between interval time and the distance each particle moves. The extracted results of the particles are shown in Fig. 16 and continuously overlapping images of tracer particles are shown in Fig. 17. Fig. 18 shows the analysis results for the movement of the tracer particles.



(a) Image of the tracer particle at the time of t [s]. (b) Image of the tracer particle at the time of t+1/60 [s].

Fig. 15. Example of images of tracer particle image.

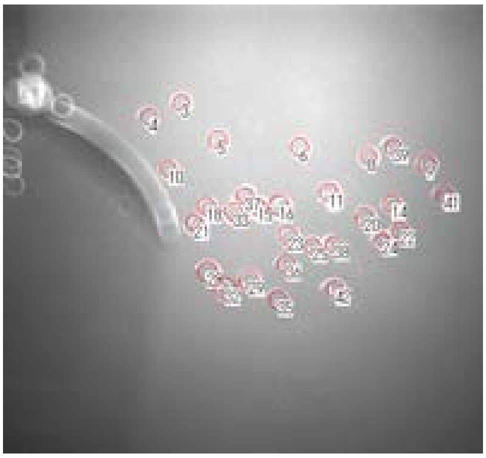


Fig. 16. Extracted result of tracer particles.

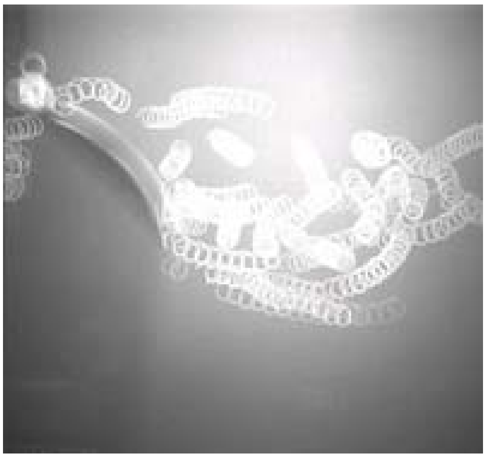


Fig. 17. Continuous image of tracer particles.

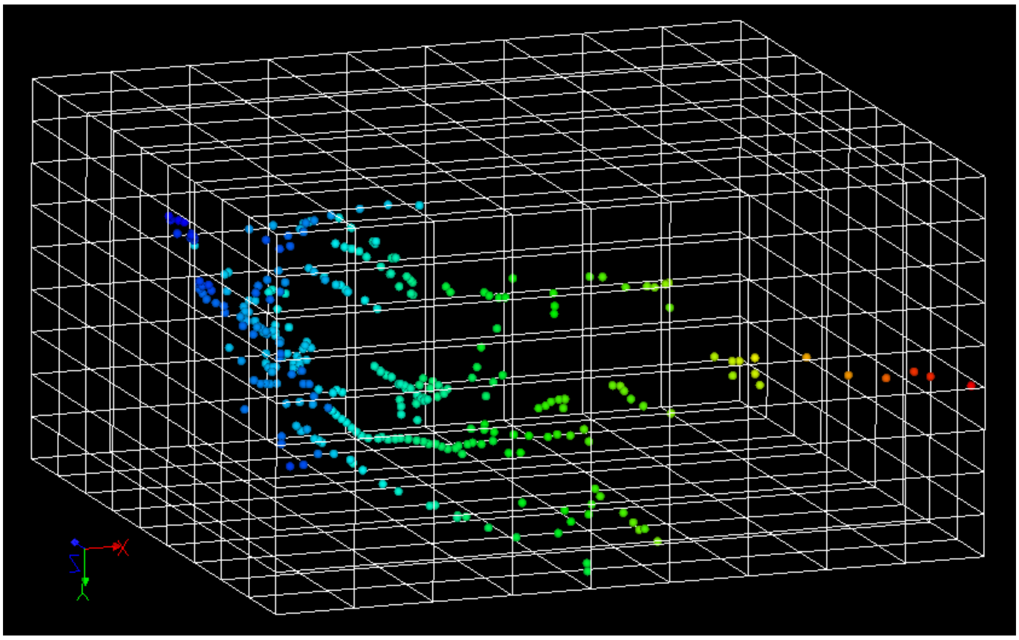


Fig. 18. Analysis result of flow measurement.

5. Conclusions

A new approach to measuring a moving surface is introduced. A characteristic of our system is that the 3-D positions of multiple points can be measured from a single image enabling a vacillating moving surface such as flowing water to be measured. A suitable calibration method for the system is developed that considers the characteristics of the system. The performance of this system was investigated and the results are presented in this paper.

Our proposed system used a CCD camera. It is also possible to use a still camera or a digital camera that has a higher resolution. Therefore, another image-capturing device could be used if more accurate measurements are required.

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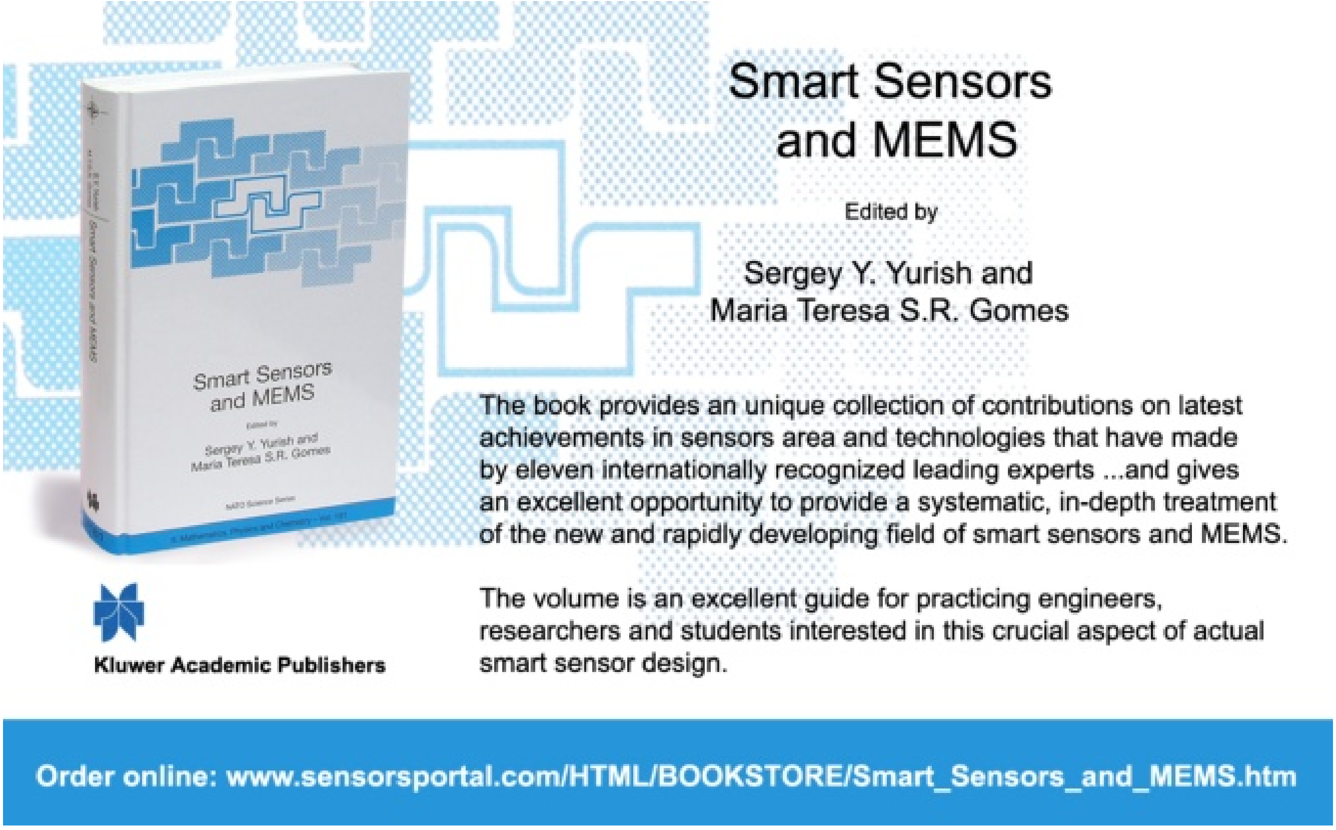

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