Circular Dynamic Stereo and Its Application

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Abstract: - By setting a refractor with a certain angle against the optical axis of the CCD camera lens, the image of a measuring point recorded on the image plane is displaced by the corresponding amounts related to the distance between the camera and the measuring point. When the refractor that keeps the angle against the optical axis is rotated physically at high speed during the exposure of the camera, the image of a measuring point draws an annular streak. Since the size of the annular streak is inversely proportional to the distance between the camera and the measuring point, the 3D position of the measuring point can be obtained by processing the streak.

In order to show the peculiarity of our system, two kinds of applications are introduced in this paper. One of them is the measurement of tracer particles in water flow and anther one is the measurement of a moving surface of water flow. These experiments prove the measuring ability of the system.

Key Words: three-dimensional, refractor, CCD camera, measurement, rotation, multiple points, image processing, calibration.

1 Introduction

The use of 3-Dimensional information obtained by computer vision system is attractive in various fields and the automatic inference of 3-D information has been and continuous to be one of the primary aims of computer vision system. In order to obtain 3-Dimensional information, some methods have been developed up to now. One is based on stereovision with two or more TV cameras and another one is based on slit-ray projection method. In stereovision method, the depth of measuring points is measured by measuring the disparity of matching pairs between frames viewed from different angle. One problem related to the stereovision is finding matching pairs between frames causes problematic computer processing since there are several possibilities for the choice of matching points. In the slit ray projection method, the measuring object is reconstructed by many images that include a structured light (slit ray) at the different position. The quantitative measurement is established by considering the geometric configuration between a TV camera and a structured light. In this method, the measuring object must be stationary while the structured light (slit ray) is scanned over the surface of the object. Therefore, moving object cannot be measured by the slit ray projection method.

In this paper, a new technique to measure the instantaneous three-dimensional positions of multiple points by analyzing a single image is introduced. The main feature of our technique is to use a single TV camera with an image shifting apparatus. By introducing a refractor on the TV camera lens, the image of the measuring point is displaced with the corresponding displacements related to the distances between the TV camera and the measuring point. When the refractor is rotated physically at high speed during the exposure of the TV camera, annular streaks of measuring points appear on an image since the rotational shift is added to the image. Since the size of the streak is inversely proportional to the distance of the measuring point from the camera, each annular streak has three-dimensional information of a measuring point. The three-dimensional information can be calculated by analyzing annular streaks. Reliable information can be obtained since our system is free from difficult matching task of measuring points between different frames.

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

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2. Measurement system

2.1 Circular dynamic stereo

A simplified setup of our imaging system is shown in Fig. 1 and the photograph of the system is shown in Photo.1. By introducing a refractor on the TV camera lens, the image of the measuring point is displaced with the corresponding displacement related to the distance between the TV camera and a measuring point. That is, the displacement *r* in the image is inversely proportional to the distance *D* between the measuring point and the camera as:

$$D = \frac{f \cdot d}{r} \qquad (1)$$

where *f* is the focal length of the camera and *d* is the magnitude of the image shifting by the refractor. When the refractor is rotated physically at high speed during the exposure of the TV camera, annular streak of a measuring point appears on an image since the rotational shift is added to the image. Since the size of the streak is inversely proportional to the distance of the measuring point from the camera, each annular streak has three-dimensional information of a measuring point. The location and the size of the annular streak in the image are related to the three-dimensional location of the measuring point.

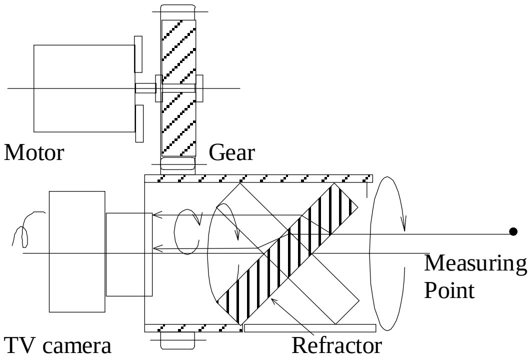


Fig.1 System setup

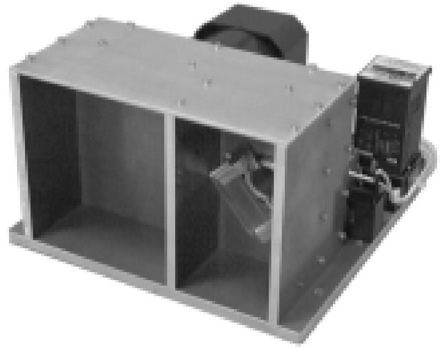


Photo.1 Circular dynamic stereo system

2.2 System configuration

The configuration of our measuring system is shown in Fig.2. The multi laser spots are projected onto the surface of the object from the position of TV camera. The laser spots on the surface of the object draw annular streaks using our system and the diameter of the streak concerns to the depth from the TV camera to the laser spot. It means that three-dimensional information of multiple points is recorded in a single image. Fig. 3.a shows the multi laser spots projected on the surface of object and Fig.3.b shows the image with circular shift by our system. Smaller annular streaks concern to laser spots on the surface of a far object and bigger annular streaks concern to laser spot on the surface of a near object.

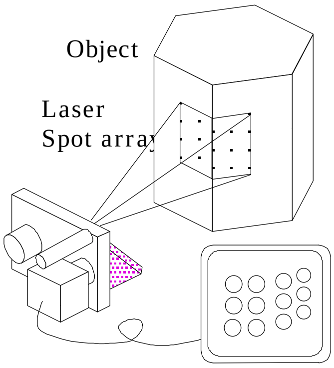
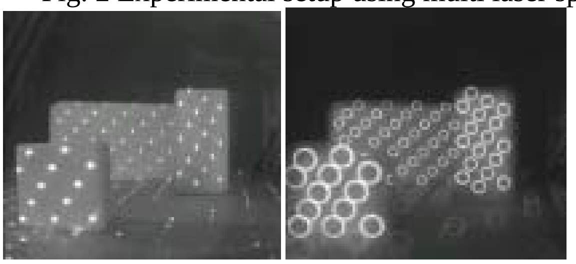


Fig. 2 Experimental setup using multi laser spots.



a. b.

a. Multi laser spots on the surface of objects

b. Image with circular shift

Fig.3 Image obtained by circular dynamic stereo

3. Calibration method

Necessary information for 3-D measuring from an image is a center position and size of each annular streak. These information, the center (u_c, v_c) and the size r_c of annular streak, are obtained by a sub-pixel accuracy using a Hough Transform [2][4][5]. The information of annular streak is converted to the world coordinate (x_f,y_f,z_f) that is fixed on the focal point of the TV camera by ,

$$\begin{bmatrix} x_f \\ y_f \\ z_f \end{bmatrix} = \frac{d}{r_c} \begin{bmatrix} u_c \\ v_c \\ f \end{bmatrix} \tag{2}$$

where d is a magnitude of shift by the refractor and f is a focal length of the TV camera.

The relationship that exists between camera coordinate and world coordinate is transformed to homogeneous coordinates as follows by setting z=s in (2).

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

The relationship between 3-dimensional points in the world coordinate system that is fixed on the measuring bench and the corresponding camera coordinate system is essentially a perspective transformation. Let the world coordinates of the object point be X,Y,Z and corresponding camera coordinates be u_c,v_c and r_c. Then the following equation is satisfied.

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

Based on the minimum squared error technique, these h_{ij} can be determined by sampling over 5 distinguished non-coplanar points, whose world coordinates are already known, with camera coordinates and the corresponding value of r.

The procedure to feed the sampling pairs onto a computer is followed. The system setup for the calibration is shown in Fig.4. Suppose the world coordinate system is fixed on the measuring bench, Y-axis and the Z-axis are on the bench, the X-axis, extending perpendicularly upward. The x,y scale is put on the surface of calibration board and the calibration board can be moved along the z stage.

1) Multi laser spots are projected on the surface of calibration board.

2) The annular streaks is recorded by the circular shifting system with band pass filter and the position (u_i,v_i) and the sizes (r_i) of each streak are estimated. (Fig.5)

3)The x,y scale on the calibration board is also recorded by the system without band pass filter at the same position.

4)The x,y scale is displayed on the monitor. (Fig.6)

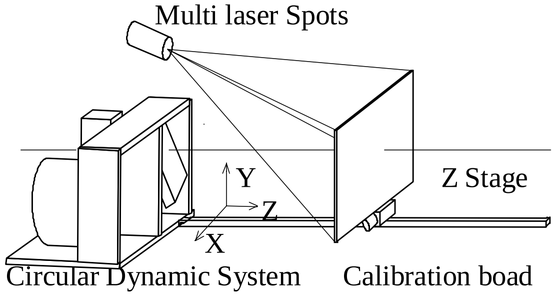
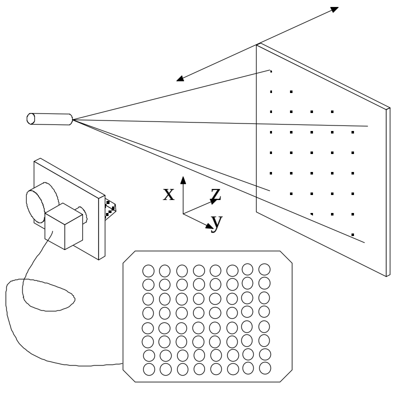
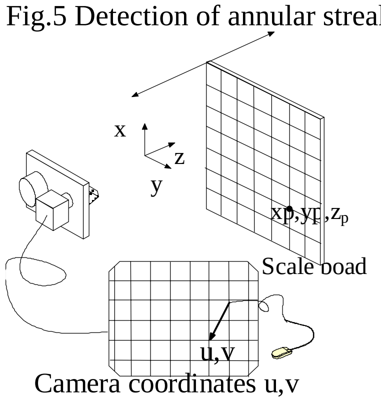


Fig. 4 Setup for calibration



Size of circular streaks (r)

Fig.5 Detection of annular streak



Camera coordinates u,v

Fig.6 Detection of pairs between coordinates

5) Camera coordinate (u_p,v_p) is fed to the computer by pointing on the x,y scale in the monitor using mouse device and corresponding world coordinate (x_p,y_p,z_p) is input by the keyboard. The value of r_p at (u_p,v_p) is determined by the size of surrounding annular streaks as:

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

where r_i is a size of the annular streak surrounding (u_p,v_p).

6) The position of calibration board is changed along z state and other pairs of coordinate are fed to computer by repeating these steps.

Rearranging (4) yields

$$Th=c$$

(6)

Where

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

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

Since the coefficient matrix T and vector h in (6) is determined by the sets of world coordinates and the corresponding camera coordinates of the over 20 distinguished points, based on the minimum squared error technique, the solution of (6) can be obtained as follows.

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

After determining the h matrix, measurement can be executed using following equation for each measuring point.

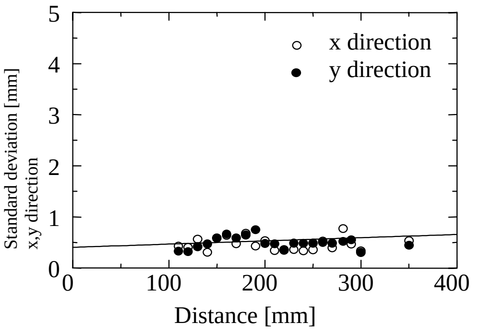
$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} h_{41}u - h_{11} & h_{42}u - h_{12} & h_{43}u - h_{13} \\ h_{41}v - h_{21} & h_{42}v - h_{22} & h_{43}v - h_{23} \\ h_{41}r - h_{31} & h_{42}r - h_{32} & h_{43}r - h_{33} \end{bmatrix}^{-1} \begin{bmatrix} h_{14} - u \\ h_{24} - v \\ h_{34}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

where (u,v) is a center point and r is a size of annular streak drawn by a measuring point.

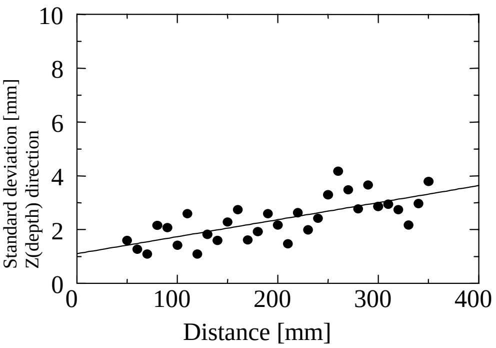
4. Experiment

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 on parallel against the image plane of TV camera at the known distance from the TV camera. The measuring point was illuminated on the surface of the board by a laser spot beam. The laser spot drew the annular streak by circular dynamic system. After the image data of circular streak was stored in the image memory (resolution is 512*512), the computer (Pentium III, 800MHz) calculates the position of the laser spot. The depth of the board was changed from 50 mm to 350mm by every 10mm. The result of this experiment is shown in Fig. 7.



x,y direction



z(depth) direction

Fig.7 Accuracy of the measuring system

4.2 Measurement of tracer particles in water flow

Experimental setup is shown in Fig.8. Tracer particles of 0.5mm, or less, in diameter are introduced in the water. The particles have a specific gravity of 1.03, so that they may be considered neutrally buoyant in water. If the rotation of refractor is fast enough than the movement of tracer particles, the particles draw annular streaks on the image plane. Fig. 9 shows the one example of particles streaks obtained by our system. In this experiment the rotational frequency is synchronized to the field frequency of TV camera (3,600 r/min). The synchronization makes computer processing easier. The size of streak relates to the depth from the TV camera. By processing the each streak, three-dimensional position of tracer particles can be obtained. In order to measure the movement of tracer particles, 24 consecutive fields are recorded. The information of motion can be estimated by the difference between these fields. Since the rotational frequency of refractor is synchronized to the field frequency, identical tracer particles draw similar streak between fields and it helps computer to find the corresponding tracer particle pair between fields. After finding particles

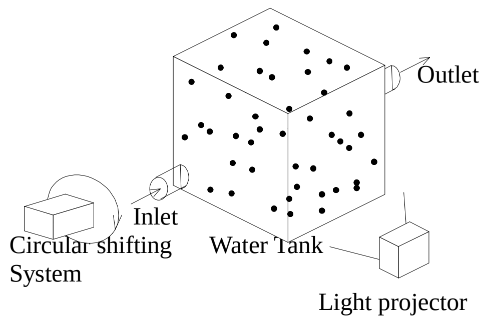
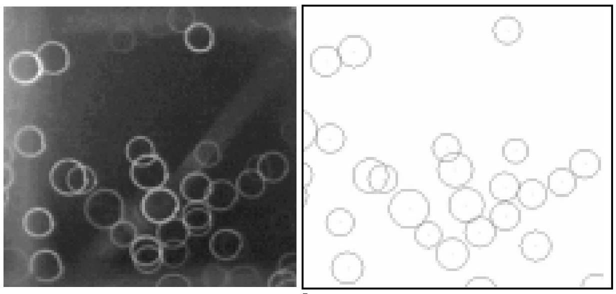


Fig.8 Experimental setup of flow measuring

pairs between fields, the difference of position and size of each streak between fields is measured to estimate the three-dimensional velocity information. The velocity distribution of flow in a tank is estimated by measuring the all particle information. Fig.10 shows the one example of velocity distribution in our experimental tank.



a. b.

a. Annular streaks of tracer particle
b. Estimated center of annular streak and extracted circle

Fig.9 Image processing of annular streaks of tracer particles in flow tank

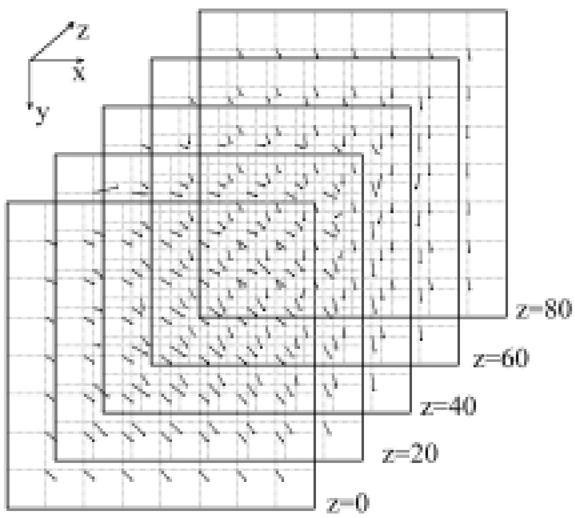


Fig.10 Three-dimensional velocity distribution in water tank

4.3 Surface measurement of a water flow

Experimental setup is shown in Fig.11. Aluminum powders (20 micro m) are introduced on the surface of flow. These powders form thin film on the surface of water and move with the wave of a water flow. Multi laser spots (30mW) are projected on the surface of water and the aluminum powder reflects these lights. Fig.12a shows the image of multi laser spots on the surface of flow. Fig. 12 b shows the image with circular shift. Fig.13 shows the reconstructed surface of water wave on consecutive two images.

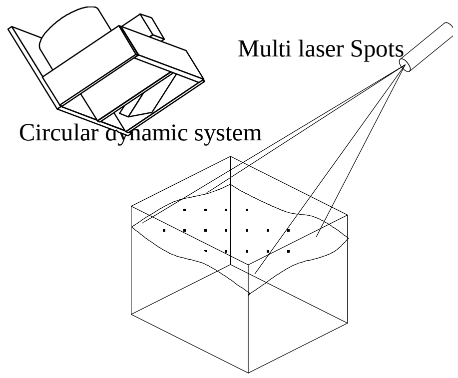
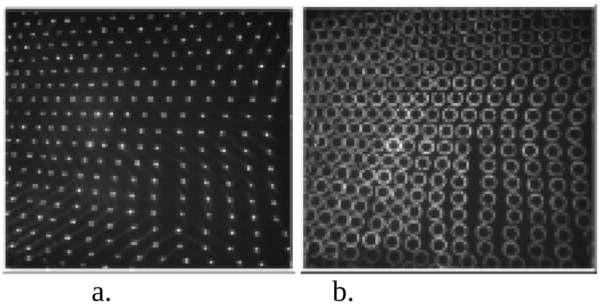


Fig.11 Experimental setup for surface measurement of flow



a. Multi laser spots
b. Multi laser spots with circular shift

Fig.12 Example image of multi laser spots on the surface of water

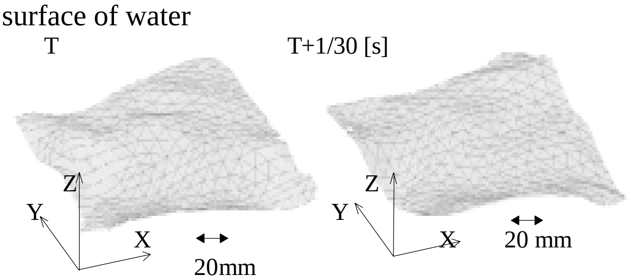


Fig.13 Experimental result of surface measurement of water wave

5. Conclusion

Circular dynamic stereo has special advantages as it enables a 3-D measurement using a single TV camera. Annular streaks are recorded using this system and the size of annular streaks directly concerns to the depth from the TV camera. That is, the size of annular streaks is inversely proportional to the depth from the TV camera and the depth can be measured by image processing technique. A calibration method of the system and the two kinds of applications were introduced in this paper. These results showed the feasibility of our system.

Acknowledgement

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