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Compact Vision Using Circular Dynamic Stereoscopy with a Beam Splitter

Application for Fluid Measurement

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Abstract : Circular dynamic stereoscopy (CDS) has special advantages for 3-D measurement as it uses a single CCD camera without cumbersome settings. In CDS, annular streaks are recorded, with their size inversely proportional to the depth/distance of the measuring point from the CCD camera. Therefore three-dimensional information can be measured automatically by image processing techniques. When the measuring points are relatively dense, streaks on the image plane overlap, making automatic processing difficult. To cope with this problem, one of the coupled mirrors is replaced by a beam splitter. The annular streaks and their corresponding center positions are then recorded on the same image as the displacement. The recording of the center positions helps in resolving the overlapping annular streaks.

In this paper, principle, calibration method and application for fluid measurement is introduced. Experimental results are presented to demonstrate the feasibility of our method.

Keywords : 3D PTV, Image processing, Three-dimensional, Coupled mirror, Beam-splitter.

1. Introduction

The automatic inference of depth/distance information is a primary aim of computer vision systems. The stereovision method and the slit ray projection method are often used for computer vision. There are, however, some limitations in the use of these systems. In stereovision systems, finding matching pairs between frames can often be problematic, particularly when there are several possible choices of matching points. When implementing the slit ray projection method, the target must be stationary while taking measurements. These systems also need sufficient space for triangulation and making measurements is cumbersome.

To address these problems, we have developed a circular dynamic stereoscopy (CDS) system (e.g., Kawasue et al., 2002) that uses a single CCD camera. When a CCD camera is moved laterally with reference to a measuring point, the amount of the measuring point displaced on the image plane is directly proportional to the displacement of the CCD camera and inversely proportional to the depth/distance from the CCD camera to the measuring point. Thus the distance between the CCD camera and the measuring point can be estimated from the amount of movement of the CCD camera and the displacement of the measuring point on the image plane. This method is known as the monocular motion stereo system (e.g., Black et al., 1990; Naavtia et al., 1976; Sandim et al., 1990; Waxman et al., 1986; William et al., 1980). Our CDS system applies a monocular motion stereo system in a very compact physical design. By setting coupled mirrors at a certain angle to the optical axis of the CCD camera lens, the image of a measuring point recorded on the image plane is displaced by an amount related to the distance between the camera and the measuring point. When the coupled mirrors are rotated physically at high speed (3,600 r/min) during the exposure of the camera, while keeping the angle to the optical axis fixed, the image of a measuring point traces an annular streak. Since the radius of the annular streak is inversely proportional to the distance between the camera and the measuring point, the 3-D position of the measuring point can be obtained by analyzing the streak. This system has been applied to the measurement of water flow.

When the measuring points are relatively dense, streaks on the image plane overlap, making automatic processing difficult. To cope with this problem, one of the coupled mirrors is replaced by a beam splitter. The annular streaks and their corresponding center positions are then recorded on the same image as the displacement. The recording of the center positions helps in resolving the overlapping annular streaks. This method has been applied to the measurement of moving tracer particles in flow analysis-with satisfactory results being obtained.

Calibration is an important task in machine vision systems since it influences the measurement accuracy. Generally, the calibration process is complicated and is not integrated with the 3-D measurement system. By using multiple laser spots and a calibration board that moves along a z-stage, we developed a suitable calibration method for our system. The method will be also introduced in this paper.

2. Circular Dynamic Stereoscopy

When the CCD camera is moves from the left to the right by a length Δx as illustrated in Fig. 1, the position of the measuring point on the image plane appears to shift from the right to the left. The amount of displacement $\Delta u = u1\text{-}u2$ on the image plane is directly proportional to the displacement Δx of the CCD camera and inversely proportional to the distance D of the measuring point from the focal point of the CCD camera. More precisely,

$$\Delta u = \frac{f \cdot \Delta x}{D} \tag{1}$$

where f is the focal length of the camera.

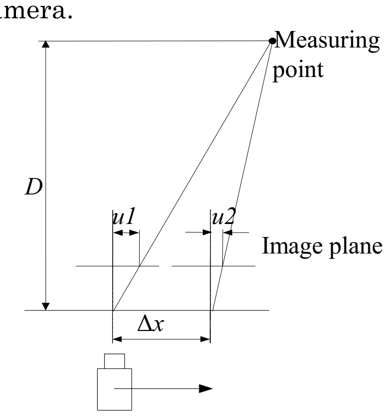


Fig. 1. Geometry of monocular motion stereoscopy.

The distance D can then be calculated from the displacement Δu on the image plane and the displacement of the CCD camera Δx. This is the technique of monocular motion stereoscopy.

To realize monocular motion stereoscopy, we developed the following system that adds a circular shift to the image. A simplified diagram of our imaging system is shown in Fig. 2 and our measuring system is shown in Fig. 3. Multiple laser spots are projected on the surface of the objects and the reflected spots are observed by our measuring system. A beam splitter and a mirror coupled to the CCD camera lens are introduced such that one image of the measuring point is directly recorded by the CCD camera through the beam splitter and a second image is displaced by traveling a path to the coupled mirror and through the beam splitter and then recorded by the CCD camera, as illustrated in Fig. 3. The magnitude of the displacement of the second image is related to the distance between the beam splitter and the coupled mirror, and the displacement of the object that appears on the CCD camera is related to the distance between the CCD camera and the 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:

$$D = \frac{f \cdot d}{r} \tag{2}$$

where f is the focal length of the camera and d is the magnitude of the image shifting of the beam splitter and coupled mirror. When the beam splitter and the coupled mirror are rotated physically at high speed during the exposure of the CCD camera, an annular streak and a center point appears as an image for each measuring point, since the rotational shift is added to the image. Figure 4 shows an example relation between measuring points and annular streaks. Since the radius of the streak is inversely proportional to the distance of the measuring point from the camera, each annular streak contains 3-D information of the measuring point. The position and the size of the annular streak in the image are related to the 3-D location of the measuring point. Figure 5a shows the multiple laser spots projected on the surface of objects without circular shift and Fig. 5b shows the image with circular shifts produced by our system. Smaller annular streaks relate to laser spots on the surface of distant objects and bigger annular streaks relate to laser spots on the surface of near objects. However, the spot inside the annular steak is not accurately located at the center of the annular streak. It is deviated slightly in the radial direction as it is apart from the center of the image. The equivalent system with rotating beam-splitter and coupled mirror is shown in Fig. 6. The deviation of the point is caused by the difference of the path-lengths between a direct path (A) through beam splitter and indirect path (B) through combination of the coupled mirrors. The spots inside the annular streak are displaced from the center in the radial direction since CCD1 is forward than CCD2. The spot is also refracted slightly by the glass of beam-splitter in the radial direction when the particle position has an angle against the optical axis. Therefore, the position ($\vec{p}'$) of the spot can be compensated as follows,

$$\vec{p}' \cong k\vec{p} \tag{3}$$

where k is a constant and $\vec{p}$ is a vector of the spot from the center in the image plane.

Image processing is relatively easy if the points being measured are relatively sparse. In cases where the points being measured are more densely grouped, for example tracer particles used in Particle Tracking Velocimetry (PTV), the streaks in the image can easily overlap each other. In order to distinguish the center from overlapped annular streaks, the center is colored by setting a red filter on the front side of a beam-splitter as it is in Fig. 3. The each center can be extracted using color image processing in the fluid measurement. However, it should be noted that the center spot can not be distinguished by the color in the case that the measuring points are illuminated by a primary color as a laser which is used in the calibration phase of chapter 3.

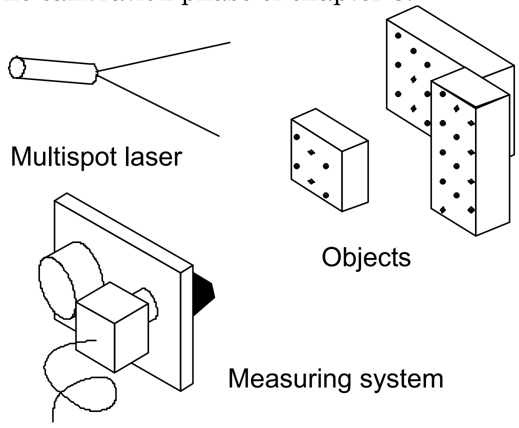


Fig. 2. Experimental setup using multi laser spots.

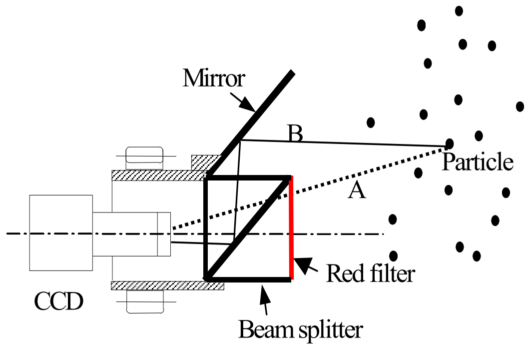
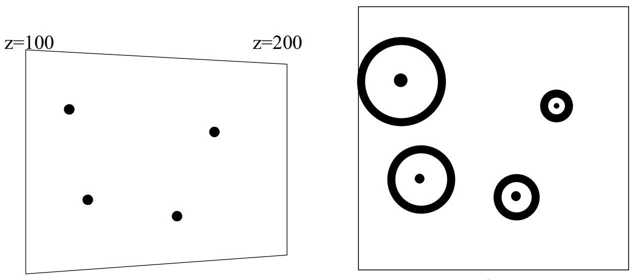


Fig. 3. Circular dynamic stereo system with rotating beam-splitter and coupled mirror.

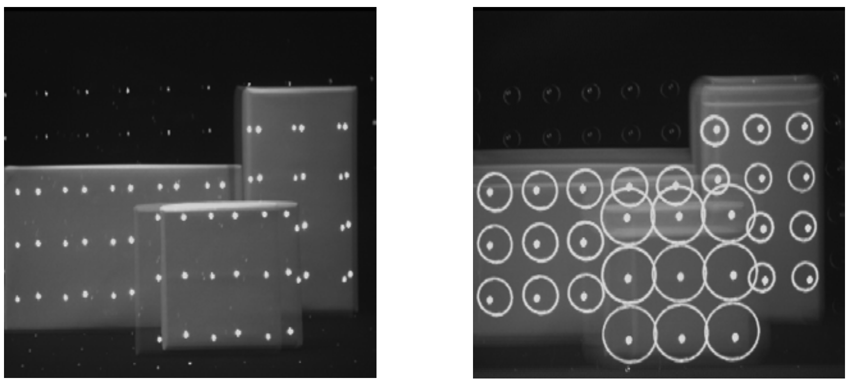


a b

a. Measuring spots on the plane board with slope

b. Annular streak and its center appeared in the image plane

Fig. 4. Relation between measuring points and streaks.



a b

a. Image without circular shift

b. Image with circular shift

Fig. 5. Image obtained by circular dynamic stereoscopy.

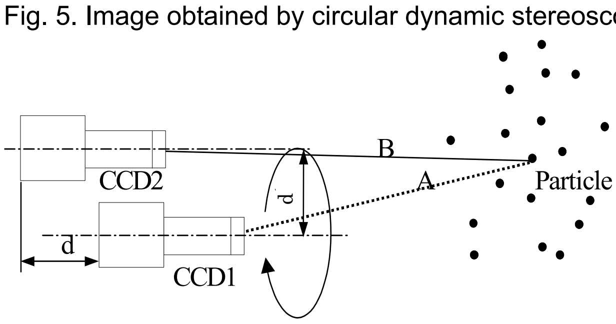


Fig. 6. Equivalent system with rotating beam-splitter and coupled mirror.

3. Calibration Method

The information required for 3-D measurement of an image is the center position and size of the annular streak. Figure 7 shows the relation between world coordinates and camera coordinates. The center (u_c, v_c) and the diameter r_c of an annular streak are obtained to sub-pixel accuracy considering the pixel intensity. The parameters of the annular streak are converted to the world coordinates (x_f, y_f, z_f) that are fixed on the focal point of the CCD camera by

$$\begin{bmatrix} x_f \\ y_f \\ z_f \end{bmatrix} = \frac{d}{r_c} \begin{bmatrix} u_c \\ v_c \\ f \end{bmatrix} \qquad (4)$$

where d is the magnitude of the shift by the coupled mirror, f is the focal length of the CCD camera, and r_c is the radius of the annular streak at this point. The values of f and d can be determined by sampling over two distinct non-coplanar points, whose world coordinates are already known.

The procedure to feed the sampling information into a computer is as follows. The system is setup for calibration as shown in Fig. 8. Suppose the world coordinate system is fixed on the focal point of the camera, the x-axis and y-axis are parallel to the image plane of the CCD camera, and the z-axis is along the optical axis of the camera. An x, y scale is placed on the surface of a calibration board that can be moved along the z stage.

1) Multiple laser spots are projected on the surface of the calibration board.
2) The annular streaks are recorded by the circular shifting system with a band pass filter and the position (u_i, v_i) and radii (r_i) of each streak are estimated using Hough Transformation (Fig. 9).

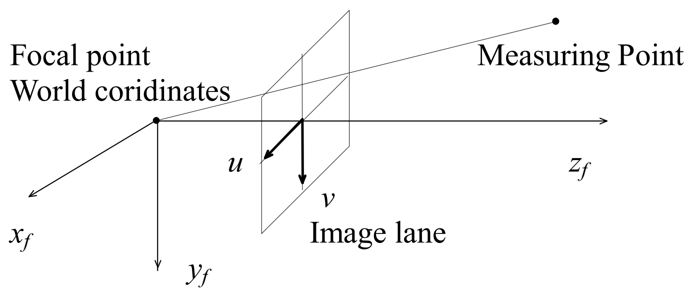


Fig. 7. The relation between camera coordinate and world coordinate.

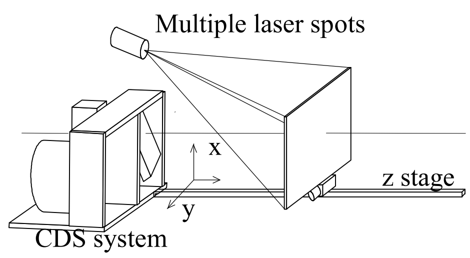


Fig. 8. Setup for calibration.

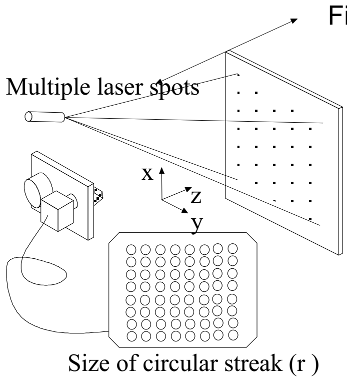


Fig. 9. Detection of annular streak.

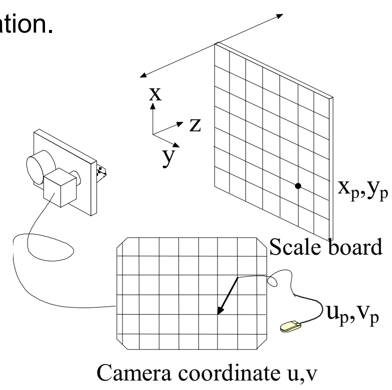


Fig. 10. Detection of pairs between coordinates.

3) The x, y scale on the calibration board is recorded at the same position by the system without a band pass filter.
4) The x, y scale is displayed on the monitor as is shown in Fig. 10.
5) The camera coordinate (u_p, v_p) is fed to the computer by pointing on the x, y scale on the monitor using a mouse device and the corresponding world coordinate (x_p, y_p) is then input via the keyboard. The z' is read from the scale on the stage. Since the position of the focal point is unknown, the following conversion is required in the later processing.

$$z_p = z' + \Delta z_p \tag{5}$$

where Δz_p is a distance between focal point and origin of the z scale on the stage.

The value of r_p at (u_p, v_p) is determined by the radius of surrounding annular streaks as:

$$r_p = \frac{\sum_i r_i \cdot \frac{1}{l_i^2}}{\sum_i \frac{1}{l_i^2}}, \qquad l_i^2 = (u_p - u_i)^2 + (v_p - v_i)^2 \tag{6}$$

where r_i is a radius of an annular streak surrounding (u_p, v_p).

6) The position of the calibration board is changed along z stage and further pairs of coordinates are fed to the computer by repeating these steps.

These data (x_p, y_p, z', u_p, v_p, r_p) are used in (4) and (5) to determine the f, d and Δz_p.

4. Experiment

4.1 Evaluation of Measuring Accuracy

To evaluate the feasibility of our system, the following experiment was conducted. A plane board was set parallel to the image plane of the CCD camera at a known distance. The measuring point was illuminated on the surface of the board by a laser spot beam. The reflected laser spot traced an annular streak in our CDS system. The image data with a resolution of 512 × 512 was then stored in a computer and the position of the laser spot was calculated. The depth of the board was changed from 200 mm to 700 mm in 10 mm steps. The results of the experiment are shown in Fig. 11. The uncertainty in the measurement of the distance was about 0.5 %.

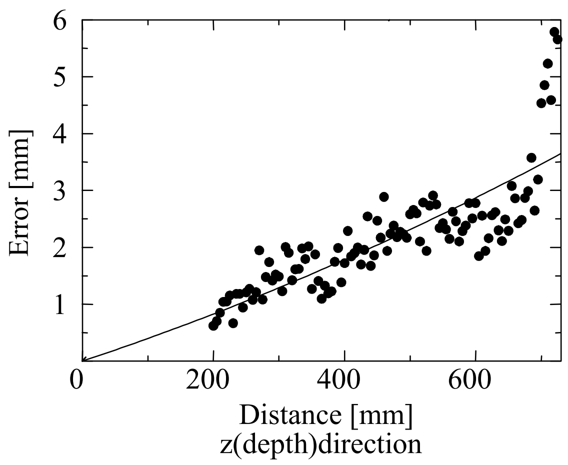


Fig. 11. Accuracy of the measuring system.

4.2 Particle Tracking Velocimetry Using Circular Dynamic Stereoscopy.

Measurement of tracer particles in water is the primary aim of this system (Particle Tracking Velocimetry) (e.g., Fujisawa et al., Lee et al., 2004). By measuring the positions of the tracer particles at different times, the three-dimensional velocity distribution within a flow can be measured. Figure 12 shows the experimental setup used to demonstrate the measuring ability of the system. The distance between the center of the tank and the measuring system is approximately 250 mm. Polystyrene tracer particles of 0.2 mm or less in diameter are scattered onto the water. The tracer particles have a specific gravity of 1.03, so that they may be considered neutrally buoyant in water. These particles are illuminated by a halogen lamp (150 W). A cylindrical tank of 200 mm in diameter is placed inside the rectangular tank and both tanks are filled with water to avoid any distortion of the image. Water in the cylinder tank is set into motion via a screw propeller driven by a motor situated on top of the cylinder tank. As the rotation of the beam-splitter and coupled mirror on the system becomes faster than the movement of the tracer particles, the particles are drawn as annular streaks in the image. An example of the particles streaks is shown in Fig. 13. Three dimensional positional information of tracer particle can be estimated by processing image. Moving information of tracer particles can be calculated by two fields taken at different times. The velocity can be calculated by finding the correspondence of streaks between these two fields. In order to help the computer processing, the beam-splitter with coupled mirror is rotated at a constant frequency (3,600 [r/min]) which frequency is synchronized with the field frequency of the CCD. The synchronization enables the computer processing easier for the correspondence as the streak-shape of each field image becomes almost the same The success rate for this correspondence is over 80 % when the velocity of particle is under 600 [pixel/s] and the number of tracer particles is under 100 on the image. The estimated velocity distribution within the cylinder is shown in Fig. 14. Velocity vectors are interpolated by taking into consideration the position of the tracer particles and the velocity vector of each tracer particle.

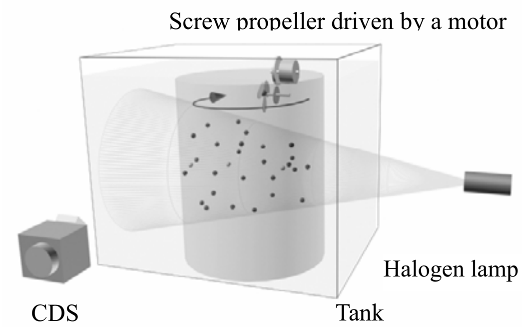


Fig. 12. Experimental setup.

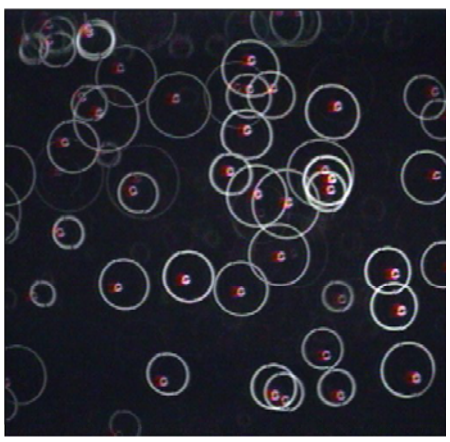


Fig. 13. Particles streaks recorded by proposed system.

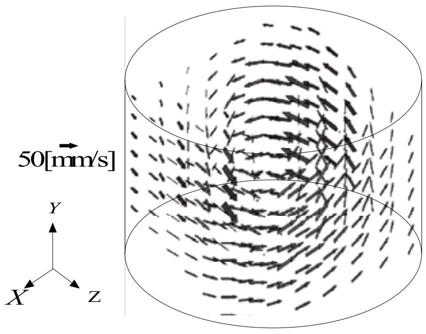


Fig. 14. Velocity distribution within the cylinder tank.

5. Conclusion

We have introduced a new approach to obtaining depth/distance information. A single camera and an image rotation apparatus record 3-D information on a single image. Annular streaks recorded on the image plane relate directly to the 3-D positional information of the individual measuring points. The 3-D information of the measuring points is obtained by using an image processing technique. The center points of each annular streak are also recorded and help extract overlapping streaks.

Our system is compact and the set up is simple since it uses a single camera. The system is thus expected to be a useful tool for fluid dynamics such as PTV. Experimental results demonstrate the feasibility of our system.

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References

Black, M. J. and Anandan, P., A model for the detection of motion over time, in third international conference on computer vision, (1990), 33-37.
Fujisawa, N., Nakamura, K. and Srinivas, K., Interaction of Two Parallel Plane Jets of Different Velocities, Journal of Visualization, 7-2 (2004), 135-142.
Kawasue, K. and Shiku, O., Shiku, Circular Dynamic Stereo and Its Application, Recent advances in simulation, computational methods and soft computing, Electrical and computer engineering series, a series of reference books and textbooks, WSEAS, (2002), 43-48.
Kawasue, K. and Ohya, Y., Circular dynamic stereo and its image processing, Advances in Multimedia, Video and Signal Processing Systems, Electrical and Computer Engineering Series, A Series of Reference Books and Textbooks, WSEAS, (2002), 36-40.
Lee, S. J. and Paik, B. G., StereoScopic PIV Measurements of Flow around a Marine Propeller, Journal of Visualization, 7-1 (2004), 25-32.
Naavtia, R., Depth measurement from motion stereo, Computer. Graphics Image Process, 9 (1976), 203-214.
Sandini, G. and Tistarelli, M., Tistarelli, Active tracking strategy for monocular depth inference over multiple frames, IEEE Trans. Pattern Anal. Machine Intell., 12 (1990), 13-27.
Waxman, A. M. and Shinha, S. S., Dynamic stereo: Passive ranging to moving objects from relative image flow, IEEE Trans. Pattern Anal. Machine Intell., PAMI-8 (1986), 406-412.
Williams, T. D., Depth from camera motion in a real world scene, IEEE Trans. Pattern Anal. Machine Intell., PAMI-2 (1980), 511-516.

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