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Automatic Extraction of Particle Streaks for 3D Flow Measurement

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Abstract

Circular dynamic stereo has special advantages as it enables a 3-D measurement using a single TV camera and also enables a high accurate measurement without a cumbersome calibration. Annular particle streaks are recorded using this system and the size of annular streaks directly concerns to the depth from 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 automatically by image processing technique. Overlapped streaks can be processed also by our method. The flow measurement in a water tank is one of the applications of our system. Tracer particles are introduced into the water in a flow measurement. Since the tracer particles flow with water, three-dimensional velocity distributions in the water tank can be obtained by measuring the all movement of tracer particles. Experimental results demonstrate the feasibility of our method.

1. Introduction

Recently, an image processing technique has been exploited to determine the instantaneous velocity field of flow. These systems determine the velocity field by measuring the displacement of tracer particles during a short time interval. The most of systems developed deals with two-dimensional flow and yields only the two in-plane components of the velocity vectors, which are measured over a planar region.

Recently, the desire to have simultaneous multi-point measurements of fluid velocity within a finite volume is very strong among both engineers and researchers in the area of fluid dynamics. The 3-D measuring system needs to yield all three components of the location and the velocity vector for each tracer particles. Stereoscopic imaging [1][2] is a 3-D measuring system, in which moving particles are recorded simultaneously from two or three different angles. Particles are triangulated individually, and are tracked from one image to the next image to recover velocity information. One difficulty of the stereoscopic imaging is to match each tracer particle among the images viewed from different angles.

In order to cope with this problem, we developed a new three-dimensional measuring system [6], which uses a single TV camera. By introducing refractor on the TV camera lens, measuring points, which appear on the image plane, are displaced according to the depth. The magnitude of displacement on the image plane is inversely proportional to the depth from the TV camera to the measuring point in the environment. Upon rotating the refractor at high speed during the TV camera exposure, these measuring points are shifted and appeared to be annular streaks on an image plane. The size of the streak directly relates to the depth of the measuring point and is inversely proportional to the depth. Three-dimensional information is obtained by processing streak images, where the cumbersome task to find matching pairs is not necessary.

In the case that many measuring points are existed in a frame, some annular streaks of measuring points overlap each other. In order to extract each annular streak from overlapped streaks, lines in the direction of edge normal are generated. Normal lines at the segment of an annular streak accumulate in the 2-dimensional parameter space. Since the annular streak has concentric segment, their normal lines converge at the center of the annular streak. The center of the each annular streak can be extracted by finding the peak generated in the parameter space. After finding the center of annular streaks, pixel intensities at any distances from the center are accumulated in another 1-dimensional parameter space and the parameter space has a peak at the distance that is equal to the radius of the annular streak. This procedure enables fast and efficient analysis of annular streaks.

Velocity distribution in a water tank is introduced for one of the applications of our system. The result proved a feasibility of our method.

2.Measurement system

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

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

where f is the focal length of the camera and d is the magnitude of shift caused by refractor. This theory is same with the theory of dynamic stereo [3][4][5]. When the refractor is rotated physically at high speed during the exposure of the TV camera, annular streaks appear on an image since the rotational shift is added to the image. Since the size of the annular streak is inversely proportional to the distance of the measuring point from the camera, the positional information of the measuring point can be obtained easily by processing the annular streak.

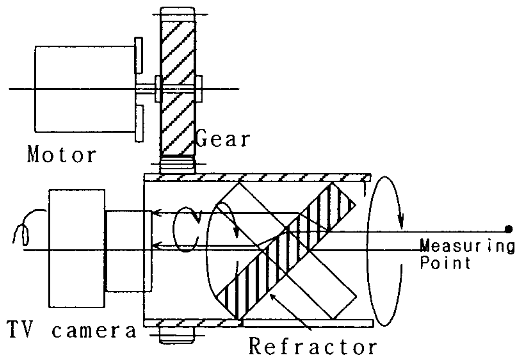
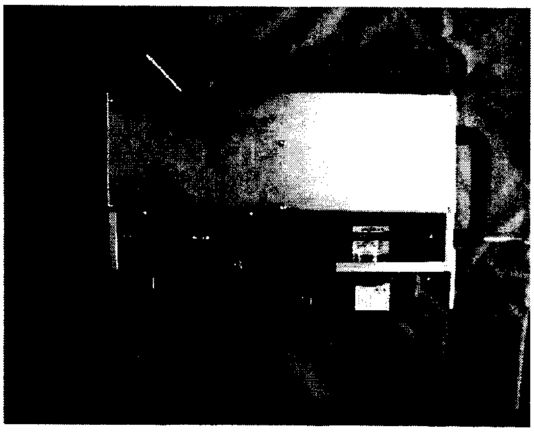
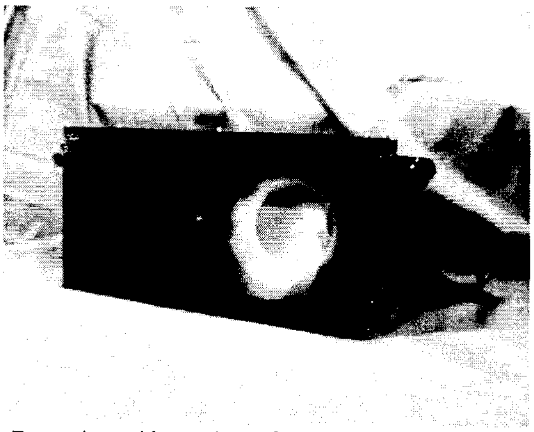


Fig.1 System Setup



Uper view



Front view with rotating refractor

Photo.1 Circular dynamic stereo system

3. Analysis of annular streak

In the case that the measuring points are dense, streaks on the image plane would be overlapped each other. Since the segment of an annular streak appearing on the image plane is concentric, each streak can be extracted automatically by the following procedures. Firstly, the intensity gradient is first estimated at all location in the image and then gated at certain threshold level to extract the positions of significant edge of circle. Next, lines in the direction of edge normal against the segment of the annular streak are generated in the 2-Dimensional parameter space. The slope of the line along the edge normal is calculated by use of the components of intensity gradient on the annular streak as,

$$\theta = \tan^{-1}(g_y/g_x) \qquad (2)$$

where g_x and g_y are the local components of intensity gradient.

Then the points along a line in the directions of the edge normal are accumulated in parameter space. Fig.2 shows an example of annular streaks and lines in the directions of the edge normal.

Since the lines in the direction of edge normal are converged at the center of annular streaks, the peak caused by this accumulation in parameter space might be interpreted as a possible center. Distinguished peaks might be extracted by setting an appropriate threshold level.

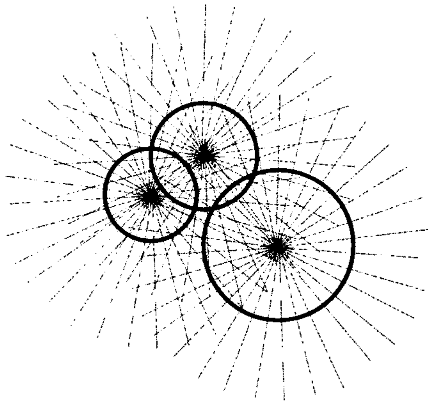


Fig.2 Annular streaks with lines in direction of edge Normal

In the above procedure, the computer accumulates not just one point per edge pixel but accumulates whole points on the line along the direction of the edge normal. It increases the number of dispersed points in a parameter plane and causes the generation of extra false peaks in practical cases. In order to cope this problem, just one point should be selected to be accumulated per edge pixel by following procedure.

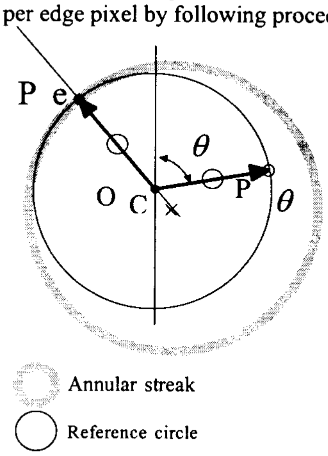
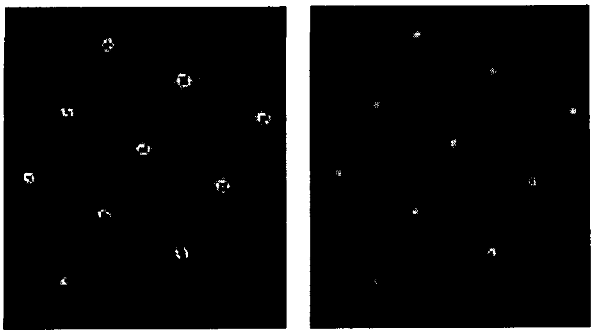


Fig.3 Examination of reliability for center candidate

In Fig.3, Oc is assumed to be one candidate point for a center of the annular streak and is located on the line along the direction of edge normal at Pe. The reliability of the candidate point Oc as a center point of the annular streak is examined by considering a reference circle of center Oc and radius $\overline{PeOc}$. If the Oc is located at the accurate center, the reference circle corresponds with the annular streak. All points on the line along the direction of edge normal for Pe are examined and only one possible point is selected and accumulated in a parameter space. The residual error between reference circle and the annular streak can be examined by

$$\phi_{Oc} = \sum_{\theta=0}^{2\pi} \left| f_{Pe} - f_{p\theta} \right| \qquad (3)$$

Here f_{pe} and $f_{p\theta}$ are intensity at point Pe and P_θ respectively. The O_c that has minimum value of ϕ_{oc} along the line in direction of edge normal can be considered as a possible center of the annular streak and be selected to be accumulated. Clear and accurate peaks can be generated in the parameter plane by the above procedure. Fig.4 shows the data in parameter plane graphically. This figure shows the effect of this method.



a. b.

a. Accumulation of lines in the direction of edge normal in parameter plane.
b. Accumulation of selected possible centers for edge pixels in parameter plane.

Fig.4 Accumulated data in parameter plane.

While an accurate center of the annular streak can be determined by using the reference circle, this method is problematic in that it needs a large amount of computations under the calculation of a residual error. To enable the faster processing, the floating threshold that is equal to the smallest residual error on the actual step, is adopted under the calculation of ϕ_{oc}. Example of growth curves under the calculation of the residual error is shown in Fig.5. If the reference circle does not correspond with the annular streak, the value ϕ_{oc} grows rapidly as -2- -3- -4- and exceeds the current threshold in early step. In this case, the calculation for this candidate point should be ceased immediately and the search for another candidate of a center should be executed. If the growth curve does not exceed the current threshold until the calculation is completed as -5-, the current threshold value is exchanged by the new smaller value ϕ_{oc}'. The adoption of the floating threshold saves a computational time of two orders of magnitude or more without loosing the accuracy.

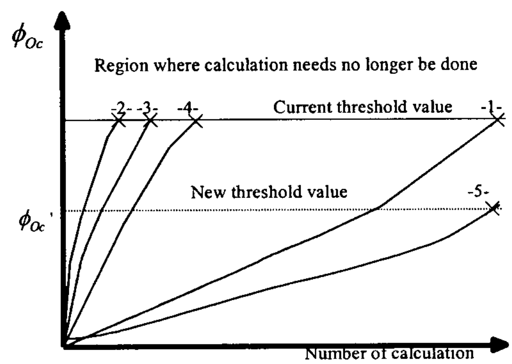


Fig.5 Growth curves of residual error between reference circle and annular streak

The parameter space is also gated at the certain threshold level to extract blobs that include a peak. Then, each blob extracted in the parameter space is labeled and the peak in the blob is found to be a center of the annular streak. The position of the peak in the blob is calculated in sub-pixel accuracy by

$$x_c = \frac{\sum x \cdot f_p}{\sum f_p} \qquad f_p > \text{certain threshold value} \qquad (4)$$
$$y_c = \frac{\sum y \cdot f_p}{\sum f_p}$$

where p is a point located at (x,y) and f_p is the amount of the accumulation of possible center at p in the parameter plane. Once all centers of annular streaks were found, each annular streak can be extracted easily regardless of their overlapping.

Since the streak is circular, the diameter of this streak can be measured many times at various angles and the final result of the diameter is obtained by taking the average. This feature of an annular streak enables a high accurate measurement. In order to simplify the procedure, the following method is used in our system.

For the first step, the accumulation of the pixel intensity where the distance is r from the center point Po is calculated by

$$F(r) = \sum_{\theta=0}^{2\pi} f(r,\theta) \,. \qquad (5)$$

where $f(r,\theta)$ is pixel intensity at (r,θ). This method is also illustrated in Fig.6. For the second step, the graph of $F(r)$ as Fig.7 is drawn by use of the results of (5). The size of annular streak r_p is determined by finding the peak in Fig.7.

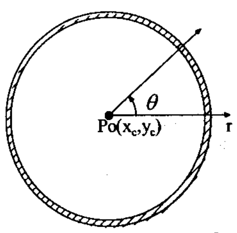


Fig.6 Measurement of the size of circular image

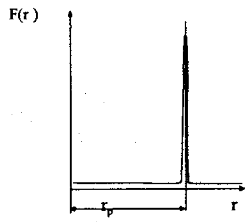


Fig.7 Accumulation of pixel intensities on r axis.

The position of peak in F(r) is calculated in sub-pixel accuracy by

$$r_p = \frac{\sum F(r) \cdot r}{\sum F(r)} \,. \qquad (6)$$

The center (x_c, y_c) and the size r_p of circular streak obtained by above procedure are converted to the world coordinate (x_w, y_w, z_w) by ,

$$\begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} = \frac{d}{r_p} \begin{bmatrix} x_c \\ y_c \\ f \end{bmatrix} \qquad (7)$$

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

3 Measurement

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.

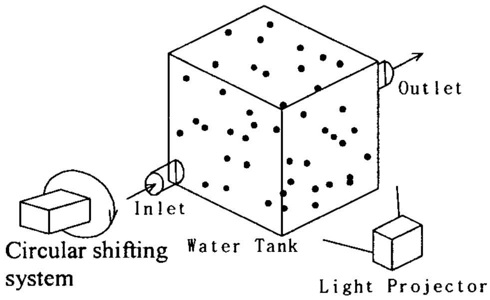
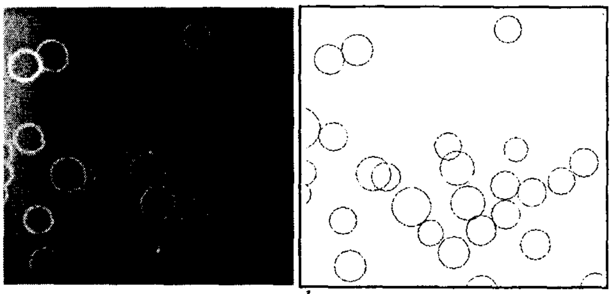


Fig.8 Experimental setup of flow measuring

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 (3,600RPM). 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 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

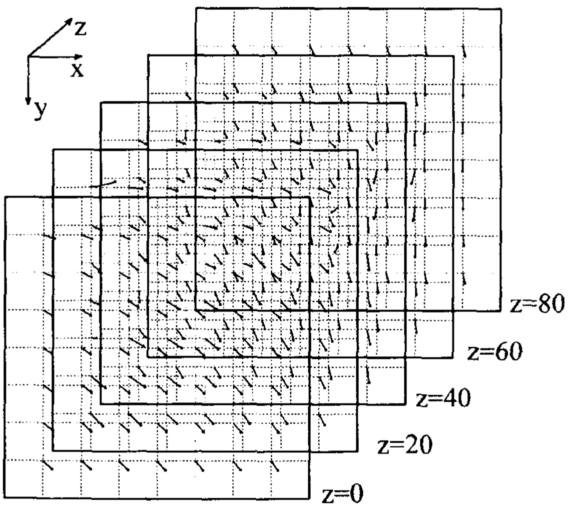


Fig.10 Three-dimensional velocity distribution in water tank

4 Conclusion

The new approach to measure the flow in the water tank is introduced. A single camera and an image rotation apparatus record the three-dimensional information on a single image.

In the case that many measuring points are existed in a frame, there are possibilities that some annular streaks are overlapped each other. By generating lines in the direction of edge normal against the segment of an annular streak, each annular streak could be extracted efficiently. Sub-pixel analysis also could be executed by considering the pixel intensity of an annular streak.

The measurement of particle positions in water flow is introduced for one of the multiple applications of our system. Our compact system can be applied for Robot vision system.

Our proposed system used a TV camera. The use of a still camera or a digital camera that has a higher resolution is also possible. Therefore, if a more accurate measurement is required, another image capturing device could be used.

Acknowledgment

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