Proceedings of the 12th
KACC, October 1997

Three-dimensional measurement of object surface and moving particles using a TV camera

Kikuhito Kawasue *, Isamu Iwamoto * and Takakazu Ishimatsu **

* Dept. of Mechanical Eng., Sasebo National College of Technology
1-1 Okishin, Sasebo, 857-11 JAPAN
Tel:+81-956-31-3261;Fax:+81-956-33-2895;E-mail:kawasue@post.cc.sasebo.ac.jp

** Dept. of Mechanical System Eng., Nagasaki University
14-1 Bunkyo, Nagasaki, 852 JAPAN

Abstract: A new approach to the three-dimensional measurement of the object surface and moving particles is introduced. A single TV camera with an apparatus to add the circular bias to the image enables us to record the three-dimensional information of measuring points as streaks on a single image. Every shape of the streak on the image plane is related to the position of the measuring point. The information is extracted from the image using an image processing technique.

Keywords: Measurement, Image processing, Three-Dimensional, Coupled mirrors, Particle

1. Introduction

The automatic inference of depth information has been one of the primary aims of computer vision system. Stereo vision that calculates the depth by analyzing two or three frames viewed from different angles is used in many cases.[1][2] The results essentially depend on how accurately matching pairs can be found between these frames. There are two problems in implementing the stereo vision. One problem related to the stereo vision is that finding matching pairs between frames causes difficult computer processing since there are, in general, several possibilities for the choice of the matching point. Another problem is a limitation of measurement accuracy in stereo vision system. The measurement accuracy is influenced directly by the resolution of the image capturing apparatus.

In order to cope with the matching problem and improve the measurement accuracy, we developed a new three-dimensional measuring system which uses a single TV camera. By introducing coupled mirrors on the TV camera lens, measuring points which appear on the image plane is displaced according to the depth. Upon rotating the coupled mirrors at high speed (1,800 rpm) during the TV camera exposure, these measuring points are shifted and appeared to be circular streaks on a image plane. The size of the circular streak directly relates to the depth of the measuring point and is inversely proportional to the depth. The depth can be measured easily by processing the circular image, where the cumbersome task to find matching pairs is not necessary. The processing required on the circular streak is to obtain the center point and the diameter. The diameter of each circular streak can be measured more than 100 times at different angles and the final result of the diameter is obtained by taking the average of them. Therefore, the accuracy is not limited by the resolution of the image capturing apparatus and the depth can be measured with sub-pixel accuracy.

One more important feature of our system is the registration of motion information of measuring points. In the case that the measuring point is moving on parallel direction with the retinal plane, the shape of the streak appeared on the retinal plane is changed from circle to spiral. Since the frequency of coupled mirrors is constant, the pitch of the spiral streak is directly proportional to the velocity of measuring point. In the case that the measuring point is moving on vertical direction with the retinal plane, the size of spiral streak is varied according to the depth. Therefore, the spiral streak has all 3-D information such as 3-D position and 3-D motion of measuring point and this information can be estimated using image processing technique.

2.Measurement system

When the TV camera moves from left to right with the length Δx as illustrated in Fig.1, the displacement of the measuring point on the image plane appears to shift from right to left.

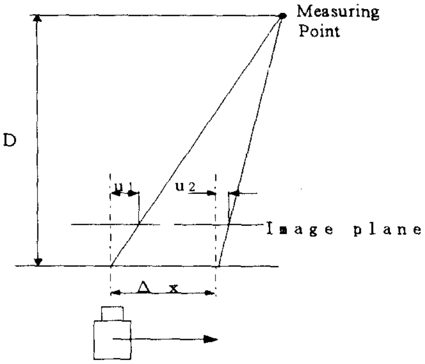

Fig.1 Geometry of monocular motion stereo

The amount of displacement Δu (=u1-u2) on the image plane is directly proportional to the displacement Δx of the TV camera and inversely proportional to the distance D of the measuring point from the TV camera. More precisely,

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

where f is the focal length of the camera. The distance D of the measuring point can be measured by knowing the displacement Δu on the image plane. This technique is well known for a monocular motion stereo.[3]-[7]

In order to realize this monocular motion stereo, we developed the following system which adds a circular shift to the image.

A simplified setup of our imaging system is shown in Fig. 2. By introducing coupled mirrors 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 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 follows.

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

where f is the focal length of the camera and d is the distance between the coupled mirrors. When the coupled mirrors are rotated physically at high speed during the exposure of the TV camera, circular streaks appear on an image since the rotational shift is added to the image.

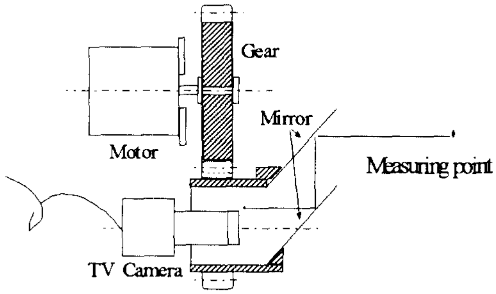

Fig. 2 System set up

Since the size of the streak is inversely proportional to the distance of the measuring point from the camera, the positional information of the measuring point can be obtained by processing the circular streak.

When the measuring point is moving in the exposure of the TV camera, the streak draws spiral streak, If a particle is moving from left to right, it draws spiral streak from left to right and the radius of streak varied depending on the variation of the distance. All spiral streaks have the same rotational direction on the image plane according to the rotational direction of the coupled mirrors. The location and the size of the spiral streak on the image are related to the three-dimensional location of the particle, and the pitch and size variation of the streak are related to the three dimensional velocity of the particle. In Fig.3, the spiral streak of a pendulum movement is shown, where it moved from a far right point to a near left point.

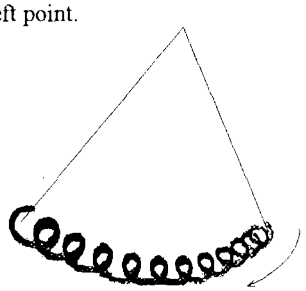

Fig.3 Path-line of a pendulum

3.Image processing

3.1 Extraction of the center point

The following processing is used to find the center point of the circular streak accurately.

By finding the maximum and the minimum position of pixels on circular streaks, the circumscribe rectangle is defined. The example of the rectangle overlapped on the circular streak is shown on Fig.4. The approximate center point Po(Xp,Yp) of the circular streak is calculated easily by finding the center point of this rectangle. The more accurate center point is detected by use of this approximate center point.

$r_{x,y}$ is a distance from the line of y=Yp on Fig.4. The top position P1 of the circular streak is calculated accurately by extracting the pixel data on the hatched band by the following equation.

$$Y1 = Y_p + \frac{\sum_{x=x_p-4}^{x_p+4} \sum_{y>y_p} f_{x,y} \cdot r_{x,y}}{\sum_{x=x_p-4}^{x_p+4} \sum_{y>y_p} f_{x,y}} \qquad f_{x,y} > \text{threshold level} \tag{3}$$

where $f_{x,y}$ is a pixel intensity on the position (x,y).

The locations of P1, P2 P3 and P4 are calculated by the same way and the center point of the circular streak is recalculated by the following equation.

$$\begin{bmatrix} x_p \\ y_p \end{bmatrix} = \begin{bmatrix} (X1 + X2)/2 \\ (Y1 + Y2)/2 \end{bmatrix} \tag{4}$$

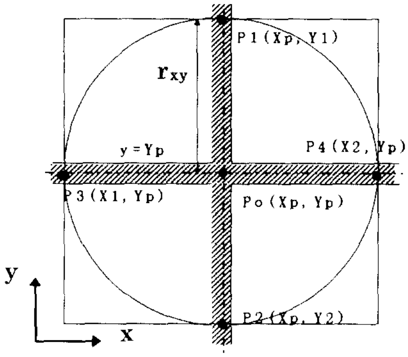

Fig.4 Extraction of the center from circular image

The amount of data to be used for extracting the center point of circular streak is reduced extremely by this technique and it enables the fast processing.

3.2 Extraction of the size of circular streak

The size r_p of the circular streak is inversely proportional to the distance between the TV camera and the measuring point. The depth can be measured by calculating the size of the circular streak. 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. In order to simplify this procedure, the following technique is used in our system. For the first step, the summation of the pixel intensity where the distance is r from the center point Po is calculated by following equation.

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

where $f(r, \theta)$ is a pixel intensity. This method is also illustrated in Fig. 5.

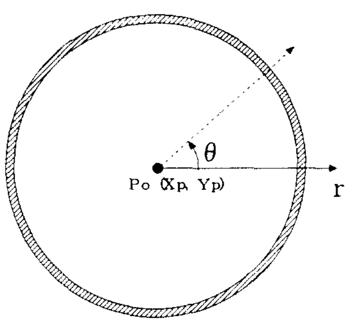

Fig.5 Measuring of the size of circular image

For the second step, Fig.6 is drawn by use of the results of (5).

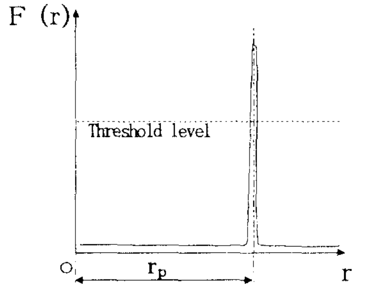

Fig.6 Intensity of pixel on r axis

F(r) over the threshold level is used to find the radius r_p of the circular streak where F(r) peaks within the graph. The r_p is calculated by (6).

$$r_p = \frac{\sum_i r_i \cdot F(r_i)}{\sum_i F(r_i)} \qquad F(r_i) > \text{Threshold level} \qquad (6)$$

3.3. Computation of spiral images

The rotational frequency of the coupled mirrors are synchronized with the frame frequency of the TV camera. It makes the shape of spiral streaks on each frame similar, which simplifies the following image processing. These processes are also robust by searching the similar shape of the streak and considering the connectivity of the spiral streak. In the image processing, one spiral image extracted on the first image is slid on the second image and compared with the second image to estimate the velocity information. Fig.7 shows the one example of extracted spiral image.

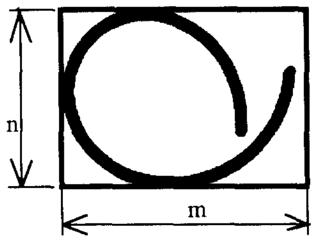

Fig.7 Extracted spiral image

The translational displacement and size variation rate between the two spiral streaks are measured by the use of the pattern matching method. After obtaining the amount of the shift of the spiral image., the coordinate on the image plane is translated to the world coordinate (x_w, y_w, z_w) by the following equation.

$$\begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} = \frac{d}{r_{i0}} \begin{bmatrix} x_{i0} \\ y_{i0} \\ f \end{bmatrix} \quad , \quad \begin{bmatrix} v_{xw} \\ v_{yw} \\ v_{zw} \end{bmatrix} = \frac{d}{\Delta t} \begin{bmatrix} \frac{x_i}{r_i} - \frac{x_{io}}{r_{io}} \\ \frac{y_i}{r_i} - \frac{y_{io}}{r_{io}} \\ \frac{f}{r_i} - \frac{f}{r_{io}} \end{bmatrix} \qquad (7)$$

where f is the focal length of the lens and d is the shift by the mirrors.

4. Experiment

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 circular streak by the rotating coupled mirrors. After the image data of circular streak was stored in the image memory (resolution is 512*512), the data was sent to the personal computer (NEC:PC-9821Xp, DX4-100MHz) and the personal computer calculate the depth of the board from the TV camera. The depth of the board was changed from 300mm to 600mm by every 50mm. The distance between mirrors was set to 40mm and focal length f of the TV camera was 3000[pixel]. The result of this experiment is shown on Fig.8.

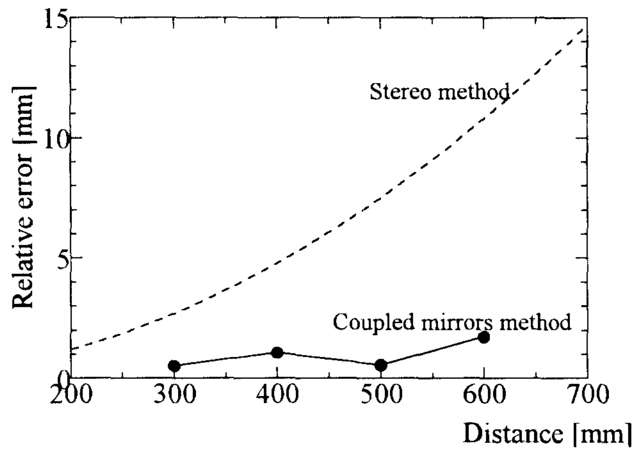

Fig.8 The experimental result of depth measurement

The graph indicates the average error [σ] of depth measurement. The dotted line indicates the theoretical error of stereo method in the case that the distance between TV cameras is same with the distance between mirrors of our system. Therefore these systems are equivalent . The theoretical error of the stereo method can be calculated using the resolution of TV camera. It means the output of the image processing is not sub-pixel accuracy, but pixel accuracy.

Fig.9 is an example of 3-dimensional surface measurement which was measured by scanning a laser spot. The depth from the TV camera was 60[cm] and 40*40 different points were measured on the surface of shells. Photo.1 is an image of measured shells and Fig. 9 is a recovered image from results. The image of Fig.9 was recovered by interpolating from the 40*40 position data.

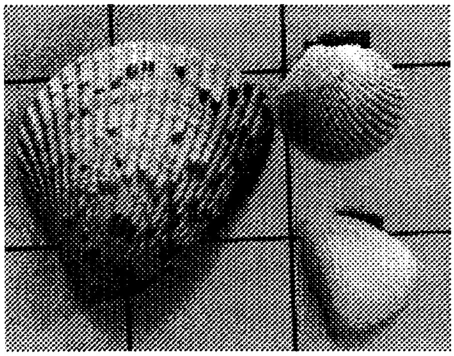

Photo.1 Measured shells

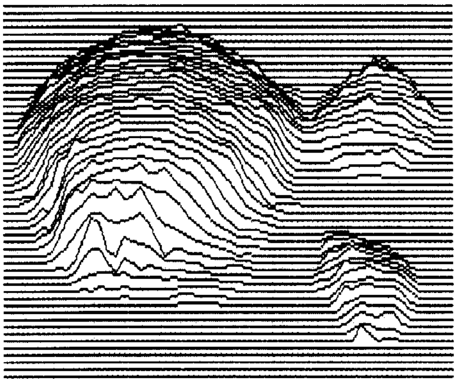

Fig.9 Experimental result

The next example is a measuring result of moving particle. The experiments are performed on the water flow field through a tank (400x250x250) with offset inlet and outlet ducts. Water is pumped and circulated through a test section. The inlet duct has a cross-section of a 1.5 cm diameter and is located at the lower-left corner. While the outlet duct has the same cross-section as the inlet at the upper-right furthest corner. The inlet flow velocity is set to 0.3 m/s in the present experiment. Polystyrene particles with 0.5 mm or less in diameter, are introduced in the water as seeding particles. The particles have a specific gravity of 1.03, so that they may be considered neutrally buoyant in water. The entire chamber is made of a clear plexiglas of 10 mm thickness so that light emitted from the projector can pass through the test chamber illuminating the particles in the flow. Fig.10 shows one example of particle streaks in a water flow field. Spiral streaks are recorded on an image. Fig.11 shows the result of the measurement in the chamber. These velocity vectors are calculated on an equidistant grid by the interpolation of the velocity data estimated from the spiral image.

5.Conclusion

The new approach to obtain the depth information is introduced. A single camera and an image rotation apparatus record the three-dimensional information on a single image. The shapes of the circular or spiral streaks recorded on the image plane relate directly to the three dimensional positional information of the individual measuring point. The 3-D information of measuring point is obtained by using an image processing technique. The image processing technique enables an accurate 3-D measurement.

The features of our system is that the system is compact and the set up is simplified since it uses a single camera. To ensure accuracy the object point needs to be illuminated by a spot light or clearly recognized from the background image.

In this paper, the proposed system used a TV camera. A still camera is also available. Therefore, if a more accurate measurement is required, a still camera should be used.

Acknowledgment

This work is in part supported by The Japan Science Society.

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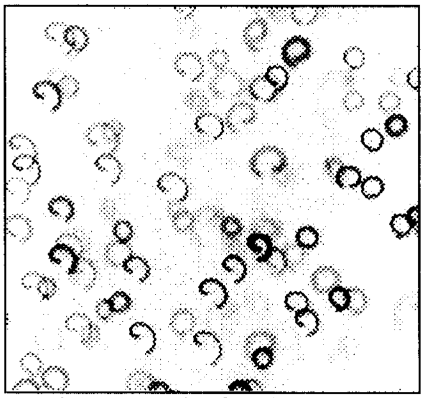

Fig.10 Example of particle images

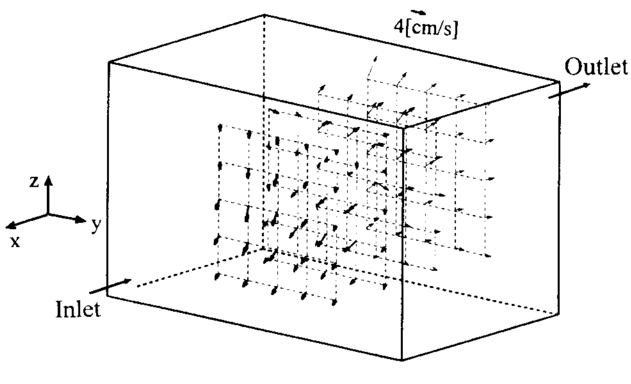

Fig.11 Velocity distribution in a chamber