Three-dimensional Measurement of Particle Movements in Micro Flow Using Circular Dynamic Stereoscopy

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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, spiral streaks are recorded, with their shape includes the three-dimensional information of moving points. Therefore three-dimensional information can be measured automatically by image processing techniques. In this paper, three-dimensional measurement method of tracer particles in a micro flow using CDS with a microscope is introduced. Experimental results show the feasibility of our method.

Key-Words: - Measurement, Image processing, Coupled mirror, Microscope, Flow, Particle, Motion

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 CCD camera. By introducing coupled mirrors on the camera lens, measuring points which appear on the image plane is displaced according to the depth. Upon rotating the coupled mirrors, these measuring points are shifted and appeared to be circular streaks on an image plane. The size of the circular streak directly relates to the depth of the measuring point. The depth can be measured easily by processing the circular image, where the cumbersome task to find matching pairs is not necessary. The three dimensional information of the measuring points can be found by processing the streaks. The each streak can be analyzed 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 rotation 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.

In this paper, three-dimensional measurement technique of moving tracer particles in a micro flow using a single microscope is introduced. The experimental result shows the feasibility of our system.
2 System setup

Fig. 1 shows a general stereo vision system. More than two CCD cameras viewed from different angles are used in the system and the parallaxes between cameras are analyzed to obtain the three dimensional information of measuring points. In order to enable a micro measurement, the use of high magnitude lens such as a microscope is required. The microscope is not only expensive but also the focus adjustments for a stereoscopy are difficult for its high magnification.

On the other hand, monocular motion stereo is one of the methods for three-dimensional measurement using a single camera [3]-[7]. This method calculated the depth by the displacement of measuring points caused by the movement of a camera. This method is free from the cumbersome corresponding task between frames since it uses just a single camera. Our CDS (Circular Dynamic Stereoscopy System) is based on this monocular motion stereo, and it realized monocular motion stereo with a compact setup. The setup of CDS is shown in Fig. 2. The system is composed with a single microscope and rotating coupled mirrors system. The view of the microscope is changed by rotating the coupled mirrors. It emulates the same effects by a single microscope as the system of two or more cameras uses. This rotation of the coupled mirrors realizes the continuous measurement. The measuring points draw streaks and the three dimensional information can be obtained by analyzing the streaks. It makes computer processing easier since the correspondence procedure of measuring points between cameras is not required.

3 Principle of measurement

Fig. 3 shows the schematic of the world coordinates in a scene and camera coordinates. The relation between the camera coordinates \((u,v)\) and world coordinates \((x,y,z)\) is as follows.

\[
\begin{bmatrix}
    u \\
    v \\
    1
\end{bmatrix}
= s
\begin{bmatrix}
    k_{11} & k_{12} & k_{13} & k_{14} \\
    k_{21} & k_{22} & k_{23} & k_{24} \\
    k_{31} & k_{32} & k_{33} & 1
\end{bmatrix}
\begin{bmatrix}
    x \\
    y \\
    z \\
    1
\end{bmatrix}
\]

(1)

where \(k_{11}-k_{33}\) can be determined by sampling over 6 distinguished non-coplaner points, whose world coordinates \((x,y,z)\) are already known with camera coordinates \((u,v)\).

Spiral streak is recorded in our system since the movement of the measuring point is added to the circular shift by the rotating coupled mirror. Fig.4 shows the example of a spiral streak in an image plane. The typed value on the streaks indicates the rotational angle of the coupled mirror. The dotted line from O to C indicates the movement assumption of the measuring points without the circular shift.

In order to obtain the three-dimensional information, the measuring point has to be recorded from two different angles at the same time. Let’s assume that the B is the midpoint between O and C. When the measuring point is recorded at A on 180 degree rotation of the coupled mirrors, the measuring point must be also recorded at B in the case that the another camera is existed at 0 degree position since the measuring point can be assumed to be a constant velocity in a short period. Therefore, the two positions of A \((u,v)\) and B \((u',v')\) are used for the triangulation.
In this case, the relation between the camera coordinates \((u,v)\) and \((u',v')\) and world coordinates \((x,y,z)\) is as follows.

\[
\begin{bmatrix}
  k_{11}u - k_{12} & k_{12}u - k_{13} & k_{13}u - k_{11} \\
k_{21}v - k_{22} & k_{22}v - k_{23} & k_{23}v - k_{21} \\
k_{31}u' - k_{32} & k_{32}u' - k_{33} & k_{33}u' - k_{31} \\
k_{31}v' - k_{32} & k_{32}v' - k_{33} & k_{33}v' - k_{31}
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix}
= \begin{bmatrix}
k_{14} - u \\
k_{24} - v \\
k_{34} - u'
\end{bmatrix}
\]  

(2)

where \(k_{11}'-k_{13}'\) and \(k_{31}'-k_{33}'\) are constant.

The world coordinates \((x,y,z)\) can be determined by feeding the pair of camera coordinates \((u,v)\) \((u',v')\).

The arcs of the spiral are recorded depend on the rotating speed of the coupled mirror. The endpoint of the each arc is detected for the analysis of the spiral streak. The procedure of the detection is as follows. The example of the arc is shown in Fig.5. The procedure uses the gravity center \(O_g(x_g,y_g,z_g)\) of the arc and the center \(O_c(x_c,y_c,z_c)\) of the rectangle which encloses the arc. The center \(O_s(x_s,y_s,z_s)\) of the spiral is lay on the extension of the straight line \(O_g\) and \(O_c\). The extension of the line is as following.

\[
\begin{bmatrix}
x_s \\
y_s \\
z_s
\end{bmatrix}
= \begin{bmatrix}
x_g \\
y_g \\
z_g
\end{bmatrix}
+ n \begin{bmatrix}
x_c - x_g \\
y_c - y_g \\
z_c - z_g
\end{bmatrix}
\]

(3)

The endpoints of the each spiral arcs are detected by rotating the line around \(O_s\) as Fig. 6. Fig. 7 shows the original image and the result of the detection of the endpoints of the arcs.

In the case that the many measuring points are existed in a frame, there are possibilities of overleaping of streaks. In order to detect each streak from overlapped streaks, approximate curve is calculated for each streak. Each measuring points are tracked along the approximated curve. The approximation formula is as follows.
\[
\begin{align*}
    x &= (r + ct) \cos \theta + (x_0 + at) \\
    y &= (r + ct) \sin \theta + (y_0 + bt)
\end{align*}
\]  

(4)

where \( r \) is radius of streak, \( c, a \) and \( b \) are constant.

Fig.8 shows the one of the example of approximated curve of streaks. Each spiral streak can be extracktred from overlapped streaks using the approximation fomula.

3 Experiment

3.1 System performance

The accuracy of the measurement was evaluated as follows. The experimental setup is shown in Fig.9. The system is composed with microscope (Magnification 80), CCD camera (Resolution 811*508) and x-y-z electronic stage. Tracer particles were in shale. The position and the movement of the tracer particles were simulated by x-y-z stages. Fig.10 shows the schematic of the optical system. The image of the measurement point is recorded through coupled mirror. The image is rotated according to the rotation of the coupled mirror. The path-line of the image forms a cone shape by the rotation and the path-line is intersected at slightly upper of the measurement plane. Fig.11 shows the recognition rate of tracer particles in the scene. Horizontal axis indicates the distance from the focus point. The rate is high around the 0 \( \mu \text{m} \) distance and it takes maximum rate around 800 \( \mu \text{m} \). Because the path-line of the image has an intersection around the 800 \( \mu \text{m} \) and the magnitude of the circular shift is smaller around the intersection. Therefore the rate of the recognition is changed by the situation of the focus and the magnitude of the shift by the coupled mirrors.

![Fig.9 Experimental setup](image)

![Fig.10 Path line of the image from the measuring point](image)

![Fig.11 Rate of recognition of the tracer particles](image)

Fig.12 shows the measurement accuracy against the x-y movement of measuring point. The error is about 1.5 \( \mu \text{m} \) under the velocity 50 \( \mu \text{m/s} \). The Fig.13 shows the depth measurement against the movement in a depth direction. The error increases over the velocity 90 \( \mu \text{m/s} \) since measuring points become out of focus.
3.2 Application for the measurement of micro flow

The flow in a water-drop was measured in our experiment. The tracer particles, the diameter is 20 micro meter or less, are suspended in the water-drop. The quantitative measurement of flow can be established by measuring the movement of tracer particle by our proposed system. Fig.14 shows the example streaks of tracer particles in the case of a slow flow and Fig.15 shows streaks in the faster flow cases. The streaks are deformed to spiral according to the velocity of the tracer particles. Fig.16 shows the velocity distribution in a water drop.

![Fig.14 Slower movements](image1)

![Fig.15 Faster movements](image2)

![Fig.16 Velocity distribution in a water-drop](image3)

4 Conclusion

Three-dimensional micro-flow measurement system was proposed. Single microscope and rotating coupled mirror system records a three-dimensional position and velocity information simultaneously by compact setup. The recorded spiral streaks indicate the three-dimensional information and the information can be extracted by the proposed image processing technique. The error was under 1 % against the velocity and it is enough for the study of the micro flow. Though relatively slow flow is measured in this experiment, faster rotation of the coupled mirror is required in faster flow.

References:
[1] Three-dimensional computer vision, A geometric viewpoint, Olivier Faugeras, 1996

