Chromatic Aberration Based Depth Estimation in a Fluid Field

Nobuhiko Mukai and Yuki Matsuura
Graduate School of Engineering, Tokyo City University, Tokyo, Japan
Email: mukai@cs.tcu.ac.jp, matsuura@vgl.cs.tcu.ac.jp

Masamichi Oishi and Marie Oshima
Institute of Industrial Science, The University of Tokyo, Tokyo, Japan
Email: {oishi, marie}@iis.u-tokyo.ac.jp

***Abstract*—One of the most challenging issues is to analyze the behavior of fluid body, and it is very difficult to capture the flow of liquid. Then, PIV (Particle Image Velocimetry) or PTV (Particle Tracking Velocimetry) are usually used in order to observe the flow in a fluid field. In PIV, tracer particles, which have some color, are thrown into the fluid body, and the scattered light reflected on the particles by irradiating laser is imaged. In fact, the frequency of the scattered light is slightly changed by the Doppler Effect, and the velocity of a particle can be measured by utilizing the fact that the frequency change is proportional to the particle velocity. On the other hand, PTV is a method to measure the particle velocity by tracking each particle in images obtained by a camera. In general, both of PIV and PTV can analyze only the 2D behavior of the particles so that some additional information is required to track the particles in 3D space such as stereo vision, de-focus of the image, and color of the particle. These systems, however, requires multiple cameras, multiple images, or multiple lights. Then, a new system has been developed, which estimates the distance from the camera to a particle by utilizing the relation between the frequencies of light reflected on the particle and the lengths to the particle. However, it is not always true that hue of color is proportional to the wavelength of light. Therefore, in this paper, we propose a depth estimation method of particle by utilizing chromatic aberration of lens and investigate the relation between the hue of color for a particle and the length from the camera. First, we measure the focal length of a particle from the camera by adjusting the height of the chromatic lens. Then, we obtain the relation between the hue of color for the particle and the length from the camera by approximating the experimental data. By analyzing the approximated calibration curve, we can clarify the relation between the hue of color and the wavelength. Finally, we can estimate the depth of the particle by using the obtained calibration curve. In addition, we measure the error between the expected value and the estimated one, and investigate the factors of the estimation error. In the end of the paper, we clarify the difficulty for the estimation of particle positions in 3D fluid field.**

***Index Terms*—depth estimation, chromatic aberration, fluid field, PIV, PTV**

Manuscript received November 17, 2017; revised April 20, 2018.

I. Introduction

In order to analyze the fluid behavior, PIV [1] or PTV [2] are usually used; however, these methods are basically performed on 2 dimensional images so that 3D position of particle is not obtained. For 3D analysis of fluid behavior, extra information is needed. Then, stereo–micro PIV measurement system has been developed [3]. This system can measure the 3D position of a particle by using stereo view, which requires multiple cameras. Then, another PTV method using deconvolution has been proposed [4]. This method needs only one camera; however, many images corresponding to different focal planes are necessary to identify the particle position in 3D space. Therefore, a new 3D PTV system using color information has been developed [5]. This approach uses multiple color-cycle gradation light, which is obtained by decomposing light emitted from a LCD (Liquid Crystal Display) projector, so that the decomposed light does not have enough intensity. Recently, another similar method that utilizes color information has been proposed [6]. The system is called rainbow PIV, and identifies the particle position in 3D space by encoding color information to the depth, assuming that particle depth corresponds to the wavelength of light reflected on the particle. However, it is not always true that hue of color is proportional to the wavelength of light reflected on the particle. Therefore, we propose a depth estimation method of particle by using chromatic aberration of lens and investigate the relation between hue of color and the distance from the camera to the particle.

II. Method

Fig. 1 shows the principle of the proposed method. White light emitted from the source passes the beam splitter, and the light focuses on different positions according to the wavelengths, after it has been passed through the chromatic lens that has a function of dichroic filter and passes only the light having specific wavelengths. Fig. 2 shows the relation between the wavelength of light and the transparency of it. The passing range is very narrow so that only some limited light can be passed through the chromatic lens. The light

doi: 10.18178/joig.6.1.59-63

reflected by each particle is transmitted into the camera through the pin hole, after it is reflected by the beam splitter. Each particle on the image has different color so that we can estimate the depth of the particle, if we know the relation between the color and the depth.

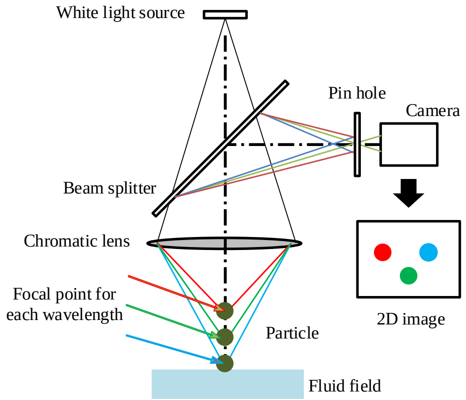


Figure 1. Overview of the proposed system.

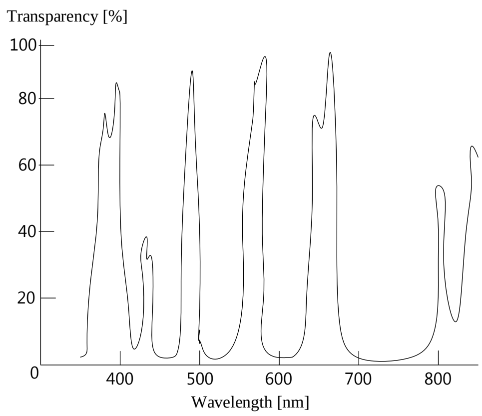


Figure 2. Relation between wavelength and transparency of chromatic lens.

On the other hand, Fig. 3 shows the depth estimation flow of a particle in 3D space. First, some calibration data, which depth is already known, are imaged by using the measurement system shown later in Fig. 4, and the calibration curve is drawn since we already know the relation between the depth of the particle and the color. Then, for the experimental data, we can estimate the particle position by using the calibration curve.

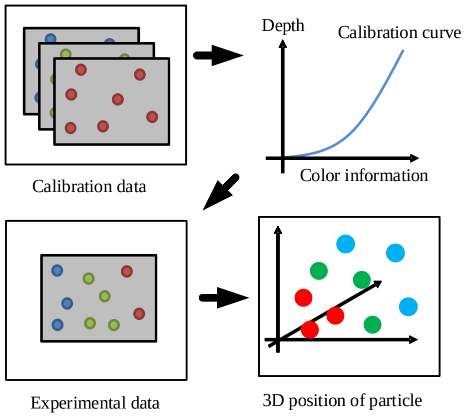


Figure 3. Depth estimation flow.

III. Depth Measurement

Fig. 4 shows the measurement system of particle depth. The micro channel with some particles is put on the glass plate and observed by the confocal microscope, where the chromatic lens is adjustable. The focal point, which corresponds to the length between the lens and the micro channel, depends on the particle color. By moving the chromatic lens, the focal point of each particle can be adjusted and the length between the lens and the particle is measured. The measured length is the distance between the lens and the particle so that the relative length is obtained by setting the minimum length as 0.

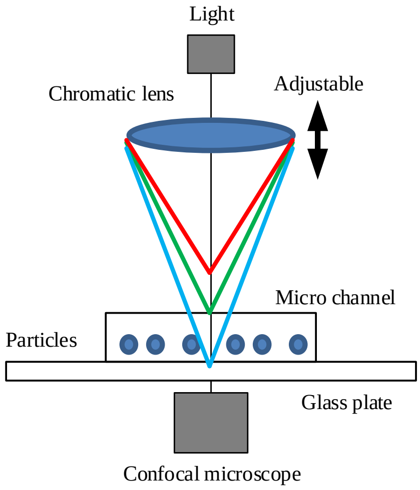


Figure 4. Measurement system of particle depth.

IV. Hue Caliculation

Color is an element of 3D space, and there are many color models such as RGB, HSV, Lab and so on. However, the representative component of a color is hue in HSV color space. Then, hue is usually used as one of the representative information of particle color. The light reflected on a particle is dispersed so that there are some hue components on the surface of a particle. Then, it is reasonable to adapt the idea that the averaged hue is used. However, the simple averaged value using only hue does not consider the saturation component of HSV color space. Then, in this research, saturation weighted average hue polar is used, which considers both hue and saturation components in HSV color space, and can be calculated as the following [5].

$$\bar{H} = tan^{-1}\left(\frac{C_2}{C_1}\right) \tag{1}$$

$$C_1 = \frac{\sum_{i=1}^{n} S_i cos(H_i)}{\sum_{i=1}^{n} S_i}, C_2 = \frac{\sum_{i=1}^{n} S_i sin(H_i)}{\sum_{i=1}^{n} S_i} \tag{2}$$

where, $\bar{H}$ is the representative color considering both hue and saturation, and S_i and H_i are the saturation and the hue of i th particle $(i = 1.2. \cdots, n)$, respectively.

V. Calibration Curve

Fig. 5 shows the calibration curve obtained from the depth measurement. The data around 0, 120 and 240 degrees show the particles of red, green and blue, respectively, and the curve is approximated by a polynomial of degree 8. From Fig. 5, we can see that the curve is not linear, and has some flat area. One reason is that chromatic lens passes only some light that has the limited wavelengths as shown in Fig. 2. Then, it seems that the flat area does not have enough sample data. The other reason is that the range of wavelength and the sensibility for each color component is different. Fig. 6 shows the relation between the range of wavelength and the sensibility of the camera, which was ARGO DFK22BUC03, having 744 × 480 [$pixel^2$] resolution. From Fig. 6, we can find that the peak of sensibility for each component is different. In addition, there is a fact that the value used for the estimation is an angle of hue ring, and the angle does not correspond to the wavelength. Fig. 6 also shows the relation between wavelength and hue angle.

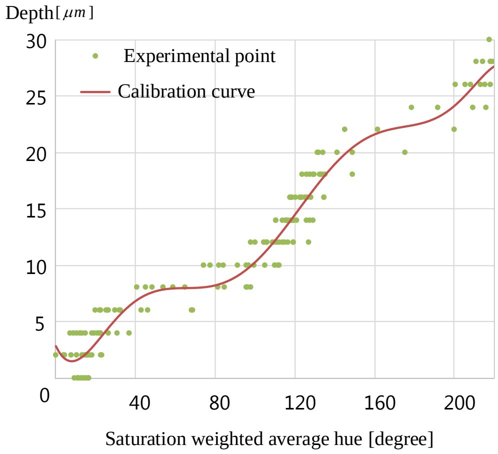


Figure 5. Calibration curve for hue and depth.

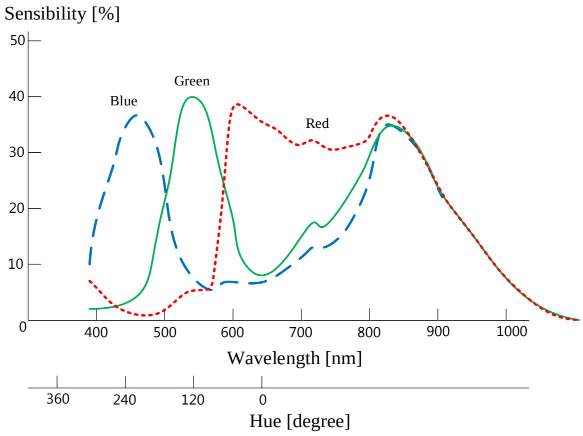
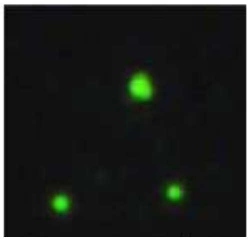


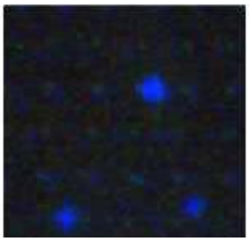
Figure 6. Relation between sensibility and wavelength or hue.

VI. Experiment and Result

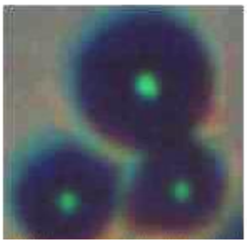
We have measured some particle depths with the proposed system. Some particle images are shown in Fig. 7. Fig. 7(a) and (b) shows the images focused at the depth of 14 [μm] and 30[μm], respectively. At the depth of 14 [μm], three green particles are clearly imaged, and at the depth of 30 [μm], three blue particles are seen although it is a little bit difficult to identify them. The reason is that there is few color difference between the background (black) and the particle (blue). These color images of particles correspond to Fig. 5, which says that green area is around 120 degrees and the depth of this area is around 14 [μm]. In addition, blue area is around 240 degrees and the depth of it is around 30 [μm]. Fig. 7(c) shows the image taken under bright field, and we can identify three particles are on the image.



(a) Image at depth 14 [μm]



(b) Image at depth 30 [μm]



(c) Image under bright field

Figure 7. Particle image.

On the other hand, Fig. 8 shows the depth of particle measured with the proposed system, which is modified with the calibration curve shown in Fig. 5. In Fig. 8, red line shows the ideal line so that the distance between the blue points (estimated depth) and the red line (expected depth) is the estimation error. The root mean square error was 1.47 [μm].

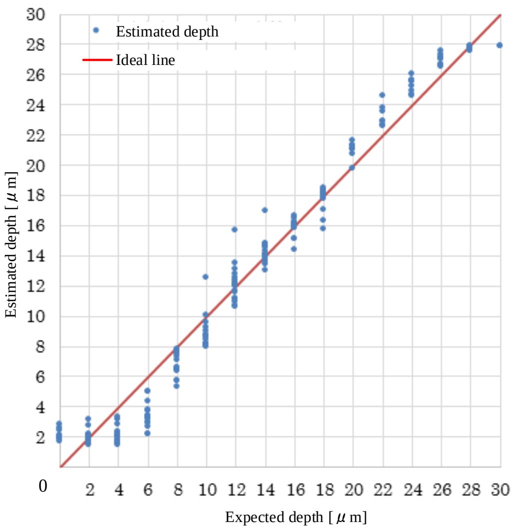
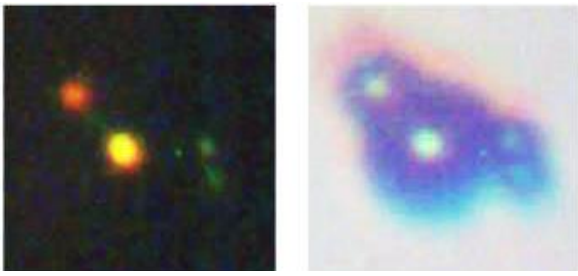


Figure 8. Experimental result.

Fig. 9 shows another example of some particle images. Fig. 9(a) is the particle image taken by the confocal microscope, and Fig. 9(b) is the image taken under bright field. From Fig. 9(a), we can see that there are some particles on the image, and even one particle has some colors on the surface. On the other hand, we can estimate that there are three or four particles on the image from Fig. 9(b). In addition, it seems that the radius of the center particle is the largest and there are two or three small particles near the center particle. The radius of particle is the same for all particles. Then, we can estimate that the center particle in Fig. 9(b) is positioned near the camera and the two or three small particles are located far from the camera. The color of the center particle has one simple color (green) from Fig. 9(b); however, the center particle has some mixed colors such as red, orange and green in Fig. 9(a). Therefore, it seems that the estimation error has happened due to these factors.



(a) Image by confocal microsope (b) Image under bright field

Figure 9. Overlapped particle image.

VII. CONCLUSION AND FUTURE WORKS

In order to investigate the flow behavior in a fluid field, PIV or PTV are usually used; however, these methods basically analyze 2-dimensional behavior. Then, some methods were proposed for 3-dimensional analysis by using stereo vison, de-focused image, and the color information of particle. Stereo vison and defocus systems need multiple images, while the method utilizing color information requires only one image. Then, some systems using color information of particle have been developed. However, it is not clear that the color information is proportional to the wavelength of light. Therefore, we have proposed a method that can measure the depth of particle in a fluid field by utilizing chromatic aberration, and tried to investigate the relation between hue of color and the wavelength. With some sample particles, we have measured the particle length from the camera and generated the calibration curve, which shows the relation between hue of color and the depth. Finally, we have experimented and measured the particle depth with the proposed system. As the result of the experiment, the root mean square error was 1.47 [μm].

By investigating the image taken by the confocal microscope and the image taken under bright field, we have found that some particles are overlapped and even one particle has some colors. Then, it has been found that there are some factors that cause the estimation error such as overlapped particle image and multiple color information for one particle. In order to improve the accuracy of the depth estimation for particle position in 3D space, more experiments are required, and also some image processing method should be created, which can divide the overlapped particles into separated one automatically. In the future, we have a plan to perform more experiments and to come up with an idea for separating the overlapped particles.

REFERENCES

[1] R. J. Adrian, "Twenty years of particle image velocimetry," *Experiments in Fluids*, vol. 39, pp. 159-169, 2005.

[2] H. G. Mass, A. Grunen, and D. Papantoniou, "Particle tracking velocimetry in three-dimensional flows, part I: Photogrammetric determination of particle coordinates," *Experiments in Fluids*, vol. 15, pp. 133-146, 1993.

[3] M. Brede, M. Witte, and A. Leder, "Stereo-micro PIV measurements of the three-dimensional separated flow in the wake of a backward facing step," in *Proc. 13th International Symposium on Applications of Laser Techniques to Fluid Mechanics*, 2006, pp. 26-29.

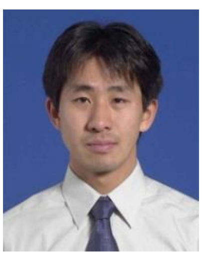
[4] J. S. Park and K. D. Kihm, "Three-dimensional micro-PIV using de-convolution microscopy," *Experiments in Fluids*, vol. 40, pp. 491-499, 2006.

[5] T. Watamura, Y. Tasaka, and Y. Murai, "LCD-projector-based 3D color PTV," *Experimental Thermal and Fluid Science*, vol. 47, pp. 68-80, 2013.

[6] J. Xiong, R. Idoughi, A. A. Aguirre-Pablo, A. B. Aljedaani, X. Dun, Q. Fu, S. T. Thoroddsen, and W. Heidrich, "Rainbow particle imaging velocimetry for dense 3D fluid velocity imaging," *ACM Trans. on Graphics*, vol. 36, no. 4, article 36, 2017.

Nobuhiko Mukai is a professor of Tokyo City University. He received his B.E., M.E. and PhD degrees from Osaka University in 1983, 1985, and 2001, respectively. He also received his M.E. from Cornell University in 1997. He started to work at Mitsubishi Electric Corporation and changed to work as an associate professor for Musashi Institute of Technology in 2002. He is currently a professor of Tokyo City University from 2007. His research interests are computer graphics and image processing. He is a member of ACM, SAS, VRSJ, IEICE , ITE, IPSJ, IIEEJ, and JSU.

Yuki Matsuura is a former graduate student of Tokyo City University. He received his B.E. and M.E. from Tokyo City University in 2013 and 2015, respectively. His research interests are image processing for fluid dynamics.



Masamichi Oishi is a technical support specialist of the University of Tokyo. He received his B.E. from Waseda University in 1998. His research interests are flow visualization and measurement of micro-multiphase flows using several optical techniques such as micro-PIV (Particle Image Velocimetry) and DHM (Digital Holographic Microscopy). He is a member of The Japan Society of Mechanical Engineers, and The Visualization Society of Japan.

Marie Oshima is currently a joint professor at Interfaculty Initiative in Information Studies and the Institute of Industrial Science at the University of Tokyo. She is also the president of the JSME (Japan Society of Mechanical Engineers) in 2017. She received her B.E. from Tsukuba University; M.E. and PhD degrees from the University of Tokyo. She also studied at MIT where she received an Engineer's degree, and was also a visiting scholar at Stanford University. She has been engaged in computational hemodynamics, flow visualization and measurements.