

Low-cost 3D-PTV utilizing rainbow light illumination and artificial neural network applied to Rayleigh–Bénard convection

Daisuke Noto^{1,2,*}, Yuji Tasaka², and Yuichi Murai²

1: Department of Earth and Environmental Science, School of Arts & Sciences, University of Pennsylvania, USA

2: Laboratory for Flow Control, Division of Mechanical Aerospace Engineering, Faculty of Engineering, Hokkaido University, Japan

*Corresponding author: dnoto@sas.upenn.edu

Keywords: 3D PTV, Color image processing, Artificial neural network, Thermal convection

ABSTRACT

Building on the novel methodology for three-dimensional (3D) color particle tracking velocimetry (PTV) proposed earlier by our research group (Noto et al., 2021), an improvement and an evaluation of the method is presented in this study. The method utilizes only a color camera and a consumer-grade liquid crystal display projector (LCDP), and thus cost for implementation is greatly lower than that required for a tomographic system. Employment of artificial neural network system enables to eliminate human decisions in constructing a color-to-depth conversion function. That is, the calibration can be performed automatically once relationship between particle color and depth are associated in actual measurement environments. The method was tested in a Rayleigh–Bénard convection of water, which is expected to have horizontally isotropic structures. Two different flow states were successfully measured. The results showed that the 3D color PTV can measure the same statistics of velocity components in the in-plane and out-of-plane directions. Considering all the results, the proposed method using only a single camera and an LCDP has a potential to be an alternative to the state-of-art tomographic measurements.

1. Introduction

Volumetric flow field measurements have been actively developed since the appearance of tomographic particle image velocimetry (PIV) (e.g. Elsinga et al., 2006; Westerweel et al., 2013). The shake-the-box method (Schanz et al., 2016) greatly reduced the ghost particle problem arising in tomographic PIV, leading to dense Lagrangian particle tracking. Nowadays, these sophisticated techniques measuring three-dimensional, three-component (3D-3C) velocity fields can be regarded as standard techniques. Of course, they can implement more advanced functions for improving their performance, such as accuracy and dynamic range, the concept of employing four or more cameras to capture 3D particle motions may not change forever. In some cases, this requirement of multiple camera installations will be a bottleneck in terms of mechanical limitation as well as its cost. In addition, for instance, tomographic PIV requires deep knowledge of advanced optics to users which are not necessary for conducting planar PIV measurements. In this sense, a simpler

and lower-cost technique yielding volumetric flow field measurements is desired to expand the applications of 3D-3C velocity field in various research fields.

One plausible solution for the problems above is utilization of light intensity information in addition to the particle positions. The concept was proposed earlier as color particle tracking velocimetry (PTV), and various methods related to the color PTV have been proposed elsewhere (Matsushita et al., 2004; Prenel & Bailly, 2006; Ruck, 2011; McGregor et al., 2007; Bendicks et al., 2011; Watamura et al., 2013; Xiong et al., 2017, 2018; Park et al., 2021). The color PTV utilizes only a camera and a light source, and the light source, such as a liquid crystal display projector (LCDP), imposes a volumetric rainbow illumination having a color gradient in the optical axis of the camera. Accordingly, it is possible to identify the depth positions of seeding particles from color information scattered due to the rainbow illumination. Combining in-plane positions of particles, 3D trajectories of the particles can be acquired based on the PTV method. Recently, we have developed an in-situ method for calibrating color-to-depth correspondences which can be conducted under actual measurement environment (Noto et al., 2021). Unlike other works introduced earlier, our method enables to directly assess the measurement accuracy thanks to the unique color-to-depth calibration method.

In this study, we will evaluate statistical performance of the 3D color PTV based on the in-situ calibration method. The method is tested in Rayleigh–Bénard convection (RBC) system, which is expected to have isotropic flow structures in the horizontal dimensions.

2. Concept of color PTV and digital slit calibration

The concept of the 3D color PTV proposed in this study is illustrated in Figure 1, and this is based on the method proposed earlier by our group (Noto et al., 2021). Spherical particles are seeded into the target flow field as like standard PIV/PTV configuration. In that system, two different measurements, calibration and main measurements, are required without changing the optical configuration.

In the main measurement, the particles are illuminated by a volumetric rainbow light emitted from an LCDP so as to have color gradient in the optical axis of a color camera. On particle images recorded during measurements, the particles with Gaussian brightness distributions are identified, and their in-plane coordinates (i, j) are determined. Color information of the identified particles is extracted, and the corresponding depth positions (y) are estimated through a certain function yielding color-to-depth conversion. The x and z positions are then computed from (i, j, y) . Finally, the particle positions in the real space (x, y, z) are acquired from a single particle image.

The key manipulation is to find an optimal function for the color-to-depth conversion in the calibration measurement, and we established a methodology using an LCDP, called digital slit calibration method. Employment of the LCDP enables a flexible illumination pattern only by varying projection digital images (animations) without changing optical configuration mechanically. Tak-

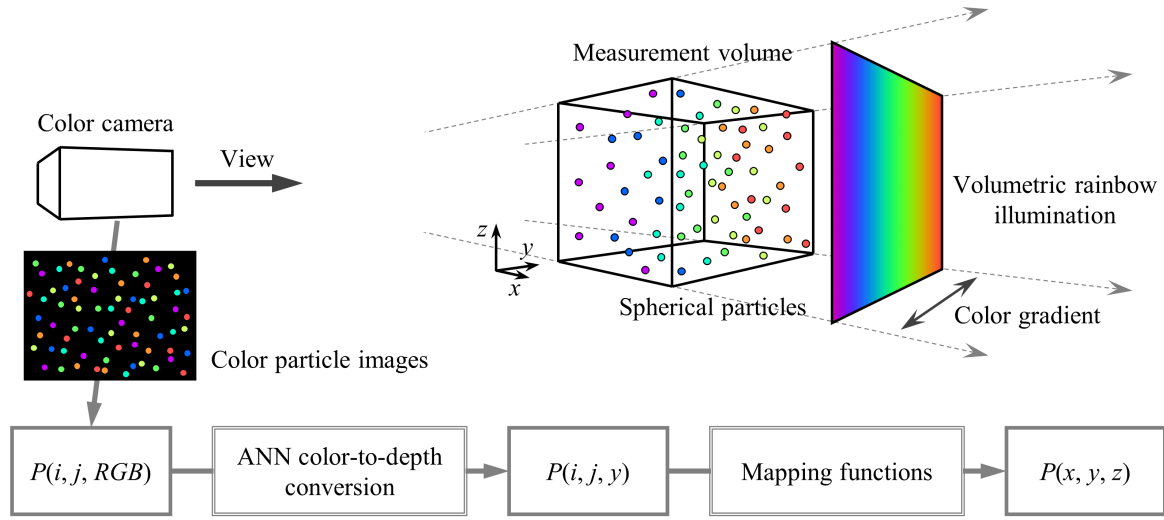


Figure 1. Conceptual image of the 3D color PTV.

ing this advantage, the color-to-depth calibration is performed by illuminating special projection patterns, which are made by slitting the original rainbow pattern. The slitted color pattern has an active region and a non-active region; the active region is a narrow region having the same color pattern as the original rainbow pattern, and the non-active region is fully black. That is, color light sheets are illuminated during the calibration measurements as if the original rainbow pattern is digitally slitted. The depth position of the light sheet in the real coordinate is easily determined from the measurement volume illuminated by the original rainbow pattern as long as the volumetric light is collimated properly.

The benefit of this digital slit calibration is that the particle colors and the corresponding depth positions are sampled under an actual measurement environment, as there is no difference in the optical configuration between the calibration and the main measurements. The calibration measurements can be done in flows of the measurement target. Accordingly, implementation of the proposed method is much easier than the other 3D measurement techniques like tomographic PIV which requires special cares for the camera alignment.

The correspondences of the particle colors and depth positions are associated via artificial neural network, since the relation will be multiple inputs (e.g., brightness values of *RGB* channels) and a single output (depth *y*). Utilization of ANN system greatly reduces efforts required for constructing calibration curves associating color values with depth, and it also enables to handle spatial trends of coloration by taking into account the in-plane coordinates (*i, j*). Summarizing above, the ANN based color-to-depth conversion takes $[i, j, R, G, B]^T$ as an input vector and returns *y* of the particles at (*i, j*). Since the present method is a single-view approach, it is required to take different magnification rates dependent on the depth positions into account. Using the obtained particle positions, (*i, j, y*), the true *x* and *z* positions are acquired via a mapping function, and finally particle positions in the real 3D system (*x, y, z*) are acquired.

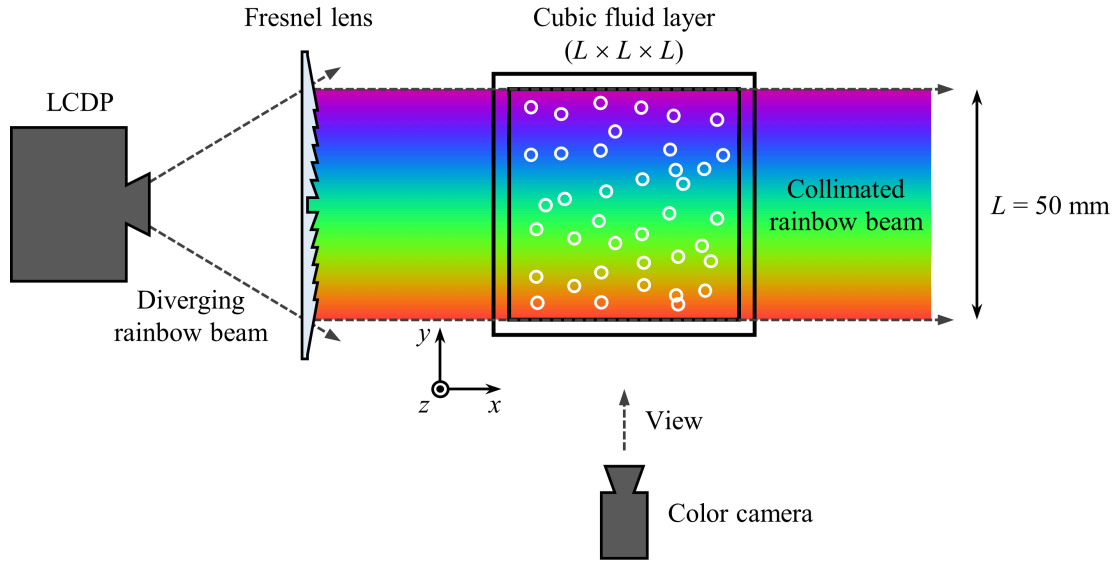


Figure 2. Schematic illustration of top view of the experimental setup.

3. Experimental design

Experimental test was conducted in an RBC system having a cubic geometry having one side as $L = 50$ mm, and a schematic illustration of the experimental setup is shown in Figure 2. Since the RBC system has cubic geometry, horizontally isotropic structures are expected. Thus, this is a good example to verify the performance of the 3D color PTV, as it is possible to directly compare the measured quantities in the x (in-plane) and the y (out-of-plane) directions. Sidewalls of the fluid container were comprised of transparent acrylic plates, and the top and bottom walls are made of copper blocks having internal cavities. Temperatures at the top and bottom boundaries are controlled independently by circulating water from thermostatic baths in the cavities. Spherical white particles, with a mean diameter of ~ 100 μm , are seeded into water. Particle number density was roughly 0.5 mm^{-3} for all the cases. An LCDP was employed as a light source and emitted a diverging rainbow beam. To ensure unique relationship between color and depth, the beam was collimated by a Fresnel lens, and the particles were illuminated. Temperature difference at the top and bottom boundaries ΔT was kept constant during each measurement condition. Accordingly, Rayleigh number, meaning the ratio of thermal buoyancy to the viscous and thermal diffusion defined as $Ra = g\alpha\Delta TL^3/(\kappa\nu)$, is fixed during the measurements. In this study, we show the cases of $Ra = 3.5 \times 10^5$ ($\Delta T = 0.2$ K) and $Ra = 1.8 \times 10^6$ ($\Delta T = 1$ K) corresponding to a laminar and a soft turbulence state. Image acquisition was made at 10 or 16 frames/s for the two experiments by a CMOS color camera. Typical particle diameter on the recorded images was 5–9 pixels, and this was sufficient to extract vivid color information utilized for the color-to-depth conversion.

One of the steps requiring a special care is selection of illuminating rainbow pattern. Many rainbow (continuously changing color) patterns have been proposed so far, and especially we found that a continuous hue change pattern produces error-prone regions in the color-to-depth relationship (Watamura et al., 2013; Park et al., 2021; Noto et al., 2021). These error-prone regions may

be originated from the presence of both steep and blunt color changes in the digital color and the depth relationship. To overcome them, we employed a new color pattern. The full rainbow pattern was compiled by providing RGB brightness values as the following equations in 24-bit format,

$$\begin{cases} r(y) &= \frac{1}{2} \left[\cos \left(a \frac{y}{L} \right) + 1 \right] \\ g(y) &= \frac{1}{2} \left[\cos \left(a \frac{y}{L} - \frac{2\pi}{3} \right) + 1 \right] , \\ b(y) &= \frac{1}{2} \left[\cos \left(a \frac{y}{L} + \frac{2\pi}{3} \right) + 1 \right] \end{cases} \quad (1)$$

where $r, g, b \in [0, 1]$ are the normalized *RGB* brightness values, and a is the range in hue value computed using the three brightness values. Please note that a needs to be set smaller than 2π because the *RGB* values are cyclic functions and $a > 2\pi$ allows to appear the same color combinations in the depthwise direction. In this study, a was set $11\pi/6$ for all the conditions. The *RGB* values provided here draws a complete circle in the 3D *RGB* domain, and thus the color change with depth y is uniform at all the depth positions.

The illumination pattern projected by the LCDP are shown in Figure 3(a), and depth-wise RGB profiles and HSV profiles (hue, saturation, and value of brightness) are shown in (b) and (c), respectively. The color pattern has a width of 720 pixels corresponding to L . Digital slit calibration was performed for each measurement condition. During calibration measurements, digitally slitted images having a sheet beam with a thickness of 20 pixels (≈ 1.4 mm) were emitted to the measurement volume. The slit position was continuously changed 5 pixels at 1 Hz, and thus 140 slitted images corresponding to the almost whole depth (≈ 50 mm) were emitted. That is, the slit position was shifted every ~ 0.35 mm. At each slit illumination, particle images were recorded for a few seconds, ensuring existence of a number of colored particles. In Figure 4, pathline images compiled at each calibration planes with different y positions are shown. Please note that the original images used to extract color-to-depth relationship are not pathlines, but snapshots of particles. Here, the we show pathline images and the color contrasts of them are adjusted for a better visibility. Clearly, it is possible to observe convective flow patterns in the images shown in Figure 4, as these calibration images were taken using the target flow fields, i.e., RBC system. Thanks to this digital slit calibration, particle colors at fixed depth can be acquired.

After acquiring the calibration images, the main measurements (flow field measurements) were conducted by illuminating the full color pattern shown in Figure 3. In this step, a full volume of the fluid layer was illuminated with a color gradient in the y -direction. The color-to-depth relationship was associated after a series of image pre-processing procedures described earlier (Noto et al., 2021). In this study, we constructed an ANN system consisting of three hidden layers with each having 500 nodes to obtain calibration function for the input, $[i, j, R, G, B]^T$ and output, y , values. Here we omit the detail of the ANN system, however, the performance of the calibration was better than ± 1 mm for all the depth-wise positions, and there was no significant error-prone region in the color-to-depth relationship, meaning the performance of the depth estimation is even at all the depth positions.

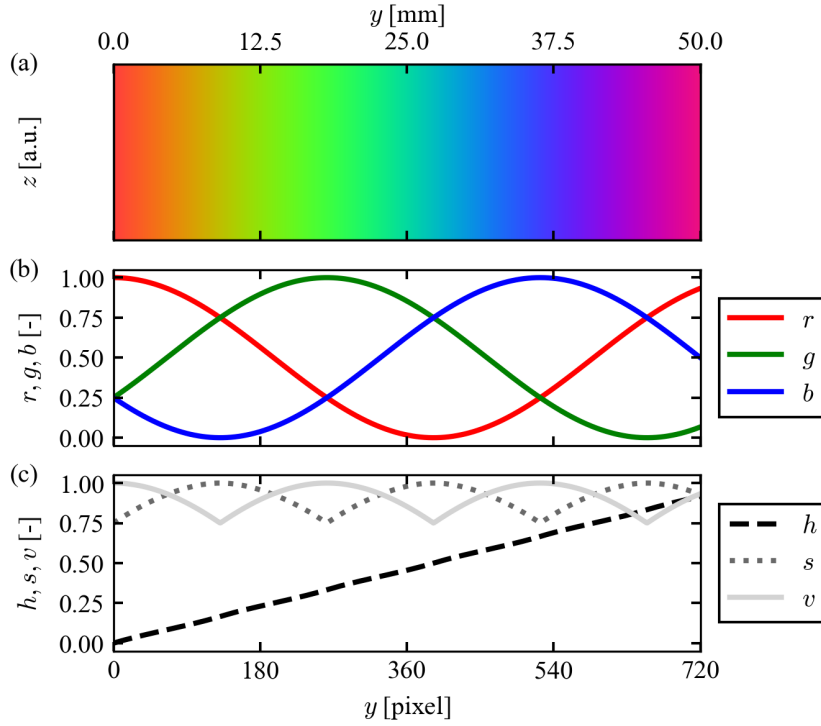


Figure 3. Illumination color pattern used for the full color illumination: (a) original color pattern, (b) normalized RGB values, and (c) corresponding HSV values.

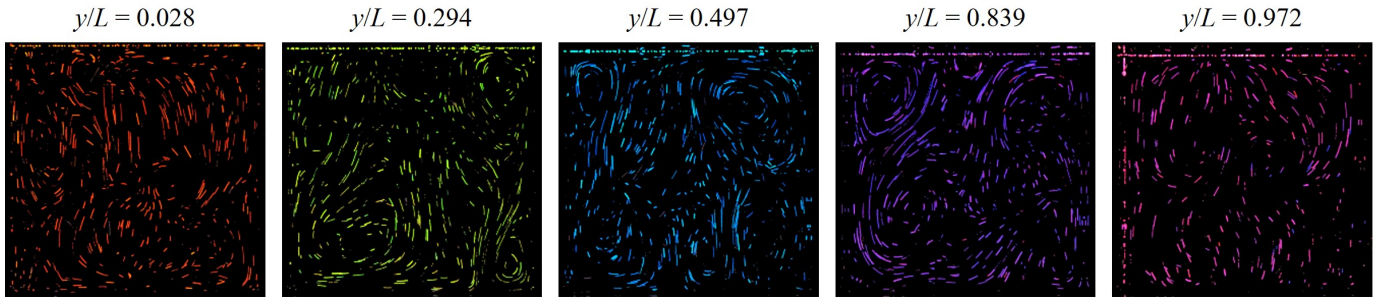


Figure 4. Examples of pathline images compiled at each calibration plane obtained during the calibration measurement. Color contrasts are adjusted for a better visibility.

4. Result

Oblique views of 3D particle trajectories obtained using the proposed method are shown in Figure 5; (a) and (b) show different Ra conditions, $Ra = 3.5 \times 10^5$ and (b) $Ra = 1.8 \times 10^6$, respectively. The trajectories are colored by the particle speed, $|\mathbf{u}| = (v_x^2 + v_y^2 + v_z^2)^{1/2}$, and note that the color ranges of the two conditions are different. In addition, the number of trajectories are reduced from the originals for the sake of clarity. In the smaller Ra condition shown in Figure 5(a), a single strong vertical flow (a group of long vertical trajectories) can be identified at around the center of the fluid layer. This vertical flow is an up-welling flow and the flow goes down at the side walls. Since the Ra is small, a single cell structure was formed. In the larger Ra condition shown in Figure 5(b), it is

possible to see a totally different structure from that shown in Figure 5(a). Compared to Figure 5(a), many strong vertical flows appear at multiple positions, and these structures can be considered as thermal plumes. It is possible to recognize a large overturning circulation dominating the whole fluid layer, the so-called large-scale circulation (LSC), and small circulations can be seen at the corners of the fluid layer. The proposed method well reconstructed typical flow features observed in a soft turbulence (Castaing et al., 1989).

The statistical performance of the proposed method is also evaluated as probability distributions of velocity components for the case of $Ra = 1.8 \times 10^6$ as shown in Figure 6. The horizontal axes are normalized by the free-fall velocity, $U_f = (g\alpha\Delta TL)^{1/2}$. Please note that the probability distributions were made using velocity data acquired during 10 times of the buoyancy timescale, $t_b = L/U_f \approx 5$ s, which is long enough time to reach statistical convergence. The shape of the probability distributions shows the Gaussian shape, and this agrees well with the flow condition (soft turbulence). It is noteworthy that the distributions in the x and y components, v_x and v_y , resemble to each other. The mean values and standard deviations noted in each panel of Figure 6 do not show significant differences. From these results, the out-of-plane velocity component v_y measured by the color-to-depth conversion can be regarded sufficiently high quality compared to the in-plane velocity components since the RBC system is horizontally isotropic in a cubic domain.

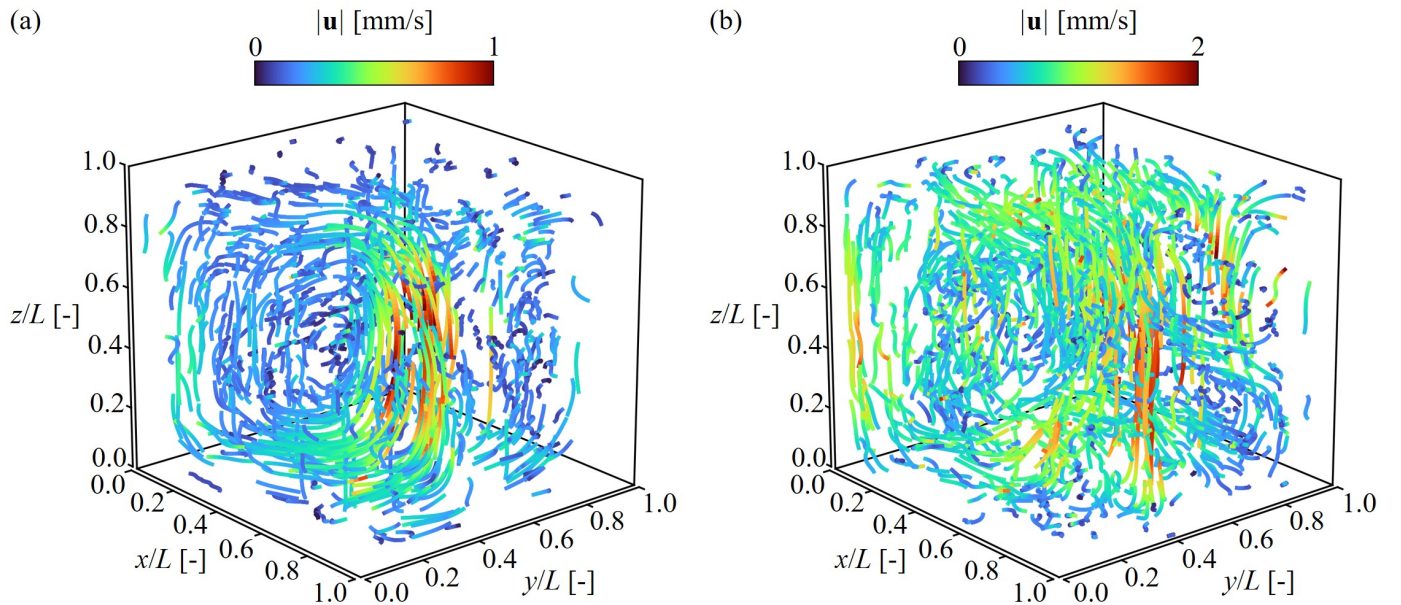


Figure 5. Examples of 3D particle trajectories measured by the present method: (a) $Ra = 3.5 \times 10^5$ ($\Delta T = 0.2$ K) and (b) $Ra = 1.8 \times 10^6$ ($\Delta T = 1$ K). The trajectories are colored by the speed $|\mathbf{u}| = (v_x^2 + v_y^2 + v_z^2)^{1/2}$ as shown in the colobars. The number of trajectories are reduced from the original data for the sake of clarity.

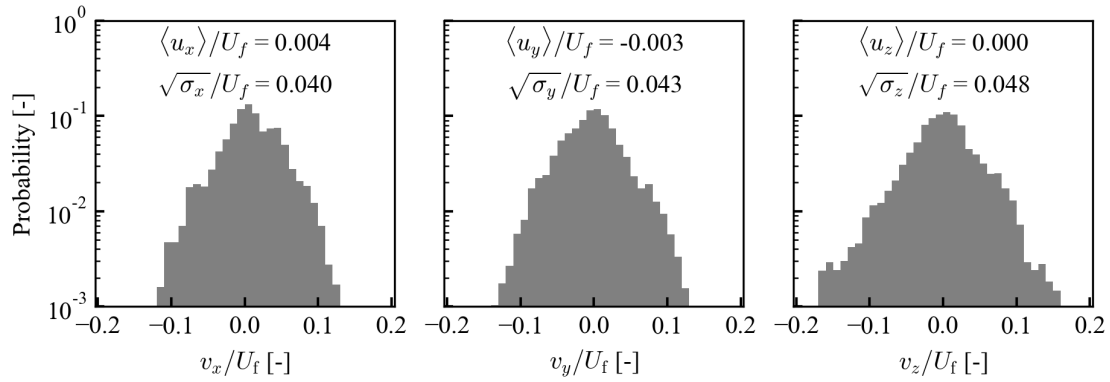


Figure 6. Probability of three velocity components for the case of $Ra = 1.8 \times 10^6$ ($\Delta T = 1$ K).

5. Conclusions

In this study, we evaluated statistical performance of 3D color PTV method based on an ANN color-to-depth calibration system and the digital slit calibration. The method uses only a single color camera and a liquid crystal display projector for 3D flow measurements. Thanks to the robust calibration procedure, the digital slit calibration, proposed earlier in Noto et al. (2021), 3D flow field measurements were possible in a Rayleigh–Bénard convection system having an isotropic flow structure. Two different flow states were reconstructed by changing vertical temperature differences of the system. From the statistics of the velocity components, the constructed measurement system is considered to have sufficiently high quality in measuring the out-of-plane velocity component only by a single color camera. Since the 3D color PTV is still under development unlike tomographic PIV, this kind of statistical evaluation is necessary to expand implementation of the 3D color PTV in various flow field measurements.

Acknowledgements

The authors are grateful to the financial supports obtained through a Grant-in-Aid for JSPS fellows (Grant No. JP19J20096) and JSPS KAKENHI (Grant No. JP21H04538).

References

- Bendicks, C., Tarlet, D., Roloff, C., Bordás, R., Wunderlich, B., Michaelis, B., ... others (2011). Improved 3-d particle tracking velocimetry with colored particles. *Journal of Signal and Information Processing*, 2(02), 59.
- Castaing, B., Gunaratne, G., Heslot, F., Kadanoff, L., Libchaber, A., Thomae, S., ... Zanetti, G. (1989). Scaling of hard thermal turbulence in rayleigh-bénard convection. *Journal of Fluid Mechanics*, 204, 1–30.

- Elsinga, G. E., Scarano, F., Wieneke, B., & van Oudheusden, B. W. (2006). Tomographic particle image velocimetry. *Experiments in fluids*, 41(6), 933–947.
- Matsushita, H., Mochizuki, T., & Kaji, N. (2004). Calibration scheme for three-dimensional particle tracking with a prismatic light. *Review of scientific instruments*, 75(2), 541–545.
- McGregor, T., Spence, D., & Coutts, D. (2007). Laser-based volumetric colour-coded three-dimensional particle velocimetry. *Optics and lasers in engineering*, 45(8), 882–889.
- Noto, D., Tasaka, Y., & Murai, Y. (2021). In situ color-to-depth calibration: toward practical three-dimensional color particle tracking velocimetry. *Experiments in Fluids*, 62(6), 1–13.
- Park, H. J., Yamagishi, S., Osuka, S., Tasaka, Y., & Murai, Y. (2021). Development of multi-cycle rainbow particle tracking velocimetry improved by particle defocusing technique and an example of its application on twisted savonius turbine. *Experiments in Fluids*, 62(4), 1–15.
- Prenel, J., & Bailly, Y. (2006). Recent evolutions of imagery in fluid mechanics: From standard tomographic visualization to 3d volumic velocimetry. *Optics and lasers in engineering*, 44(3-4), 321–334.
- Ruck, B. (2011). Colour-coded tomography in fluid mechanics. *Optics & Laser Technology*, 43(2), 375–380.
- Schanz, D., Gesemann, S., & Schröder, A. (2016). Shake-the-box: Lagrangian particle tracking at high particle image densities. *Experiments in fluids*, 57(5), 1–27.
- Watamura, T., Tasaka, Y., & Murai, Y. (2013). Lcd-projector-based 3d color ptv. *Experimental Thermal and Fluid Science*, 47, 68–80.
- Westerweel, J., Elsinga, G. E., & Adrian, R. J. (2013). Particle image velocimetry for complex and turbulent flows. *Annual Review of Fluid Mechanics*, 45, 409–436.
- Xiong, J., Fu, Q., Idoughi, R., & Heidrich, W. (2018). Reconfigurable rainbow piv for 3d flow measurement. In *2018 IEEE International Conference on Computational Photography (ICCP)* (pp. 1–9).
- Xiong, J., Idoughi, R., Aguirre-Pablo, A. A., Aljedaani, A. B., Dun, X., Fu, Q., ... Heidrich, W. (2017). Rainbow particle imaging velocimetry for dense 3d fluid velocity imaging. *ACM Transactions on Graphics (TOG)*, 36(4), 1–14.