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3D3C RAINBOW PARTICLE TRACKING VELOCIMETRY: MULTI-CYCLE RAINBOW PATTERN USING COLOR SPACE AND IN-PICTURE TRACKING TO IMPROVE VELOCITY VECTOR ACQUISITION

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ABSTRACT

Three-dimensional three-component (3D3C) rainbow particle tracking velocimetry (PTV) is a low-cost measurement technique with a single color camera. A rainbow color pattern is used as a light source, and the depth position of a particle is determined by its color. However, low depth accuracy and a low vector acquisition rate are the main issues in capturing turbulent and shear flows. In this paper, two new ideas are described and applied to 3D3C rainbow PTV. First, a multi-cycle rainbow pattern is designed instead of the original rainbow pattern. Using more color spaces improves the accuracy of depth determination. Second, tracking is carried out in a raw picture instead of three-dimensional space. Tracking rates are improved by tracking a particle on the basis of accurate x and y positions (horizontal and vertical in picture) and using color information as an aid. Moreover, for up to two time steps, the tracked particle is allowed to be lost and compensated using the information from the previous and next positions. This process significantly improves the tracking rate and number of continuous tracking time steps. 3D3C circular flow is measured in an application test. The number of successive tracking time steps is significantly improved in all three velocity ranges. Improvement in velocity vector accuracy is confirmed with the averaged circular velocity field.

INTRODUCTION

The aim of this study is to improve the accuracy of determining the velocity vector in the depth direction and the number of velocity vectors acquired to capture turbulent and shear flows in three-dimensional three-component (3D3C) Lagrangian velocity measurements using rainbow particle tracking velocimetry (PTV) with a single color camera. To achieve this, we apply two new ideas to rainbow PTV. The first involves a multi-cycle rainbow color pattern using color space. The second is a new in-picture tracking method that uses raw particle images instead of tracking in a three-dimensional domain.

3D3C velocity measurements usually require multiple viewpoints with multiple cameras, e.g., scanning tomographic particle image velocimetry (Casey et al., 2013) and the shake-the-box method (Schanz et al., 2016). Rainbow PTV (Watamura et al., 2013) is a low-cost method to obtain 3D3C velocities with a single color camera and simple data processing. The volume flow is illuminated by multi-colored light that changes along the depth direction using a liquid crystal display (LCD) projector. The depth (z) of a particle is determined by its color. The degree of hue (H, 0–360) is calculated from the RGB values of the particle and then converted to the corresponding depth position.

Although the resolutions in the two directions of the focal plane are equal to the number of camera pixels—usually more than 1000—or 10 times the number in sub-pixel analysis, the spatial resolution in the depth direction is much lower. To increase it, we apply a new multi-cycle rainbow color pattern. Colors are represented not only by RGB, but also by hue, saturation and value. Thus far, only hue has been used to determine depth, and while it is difficult to use value for determination, saturation is a sufficiently usable parameter. The new pattern contains a multi-hue cycle and different saturations, as proposed in Figure 1.

PTV provides Lagrangian velocity data at random locations. However, to assess turbulent and shear flows, it is necessary to replace these velocity data with grid data such as results from CFD or PIV measurement. This requires the acquisition of spatially dense velocity vectors. In addition, for 3D3C measurements with a single camera, time completion is required to compensate for the low resolution in the depth direction (Noto et al., 2021; Aguirre-Pablo et al., 2019), which also requires continuous particle tracking for long time steps. Tracking refers to the linking of identical particle images between successive time steps, which becomes more difficult with higher particle number density and greater particle movement in one time step. The new tracking process, described later, improves not only the tracking rate but also the number of continuous tracking time steps, and increases the number of acquired vectors.

This paper describes two ideas that improve the accuracy of depth determination and the particle tracking rate of 3D3C rainbow PTV. These are then demonstrated in an experiment with rotating flow in water.

MULTI-CYCLE RAINBOW PATTERN WITH COLOR SPACE

The color of the captured particle, i.e. the RGB values, is converted to the degree of hue through the following equation and then to depth using a pre-prepared calibration curve:

$$H = \begin{cases} 60 \times \dfrac{G-B}{max(R,G,B)-min(R,G,B)} & (\text{if}\, max(R,G,B)=R) \\ 60 \times \dfrac{B-R}{max(R,G,B)-min(R,G,B)} + 120 & (\text{if}\, max(R,G,B)=G) \\ 60 \times \dfrac{R-G}{max(R,G,B)-min(R,G,B)} + 240 & (\text{if}\, max(R,G,B)=B) \end{cases} \tag{1}$$

Depth positions derived from color information are far less accurate than x and y positions derived from particle images, so a significant improvement in accuracy is required.

Figure 1 shows the color pattern and its RGB component and ratios on a triangular graph. In the upper left panel is a triangular graph of the original rainbow pattern, where the colors used are located only on the periphery, leaving the central color space vacant, i.e. available for determining depth position. We therefore propose the new pattern shown in the lower panel. Two rainbow cycles are added to the unused color space, and the number of cycles is determined by the degree of saturation defined by the following equation:

$$Rn = R/(R+G+B)$$
$$Gn = G/(R+G+B)$$
$$Bn = B/(R+G+B)$$
$$S = [(Rn-1/3)^2+(Rn-1/3)^2+(Rn-1/3)^2]^{1/2} \tag{2}$$

R_n, G_n, and B_n are the RGB values normalized by the total value.

In the right upper panel, which shows the component of each channel, RGB values change linearly. This makes specific sections where the depth position accuracy is significantly lower. To mitigate this, the intensity transition is curved, as shown in the bottom right panel. This is called a gamma curve, and in this case, gamma = 2.

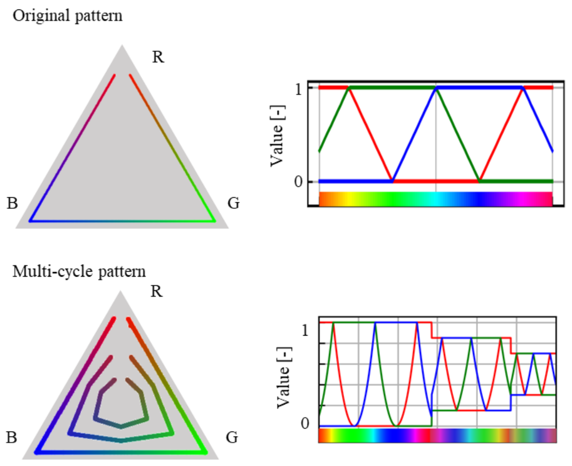


Figure 1. Original and multi-cycle rainbow patterns.

IN-PICTURE TRACKING METHOD

When the tracking process, i.e. the identification of the same particles between successive time steps, is carried out in three-dimensional space, the tracking rate is very low because of the lower depth resolution due to determination by color. Therefore, the particle is tracked on the 2D image using particle color information as an aid and then transformed into 3D space, thereby improving the tracking rate and the number of velocity vectors obtained. On the basis of a four-time-step method, the particle position is predicted from positions up to the previous time steps and filtered using color information for particles within the search area around it. After tracking, the inaccuracy of the z position obtained from the colors is compensated by a polynomial approximation of the z position time series before it is converted to 3D position information (Noto et al., 2021; Aguirre-Pablo et al., 2019). Long-term continuous tracking is required for approximation, so only particles tracked continuously for more than 10 steps are considered here.

The main cause of tracking failure is particle overlap. Multiple overlapping particles are recognized as a single particle with mixed color information, producing the sample in Figure 2. In three consecutive images, independently moving green and orange particles (circled in white) overlap at the middle time step. It is currently impossible to determine that the overlapping particles are two particles and furthermore to extract their respective colors.

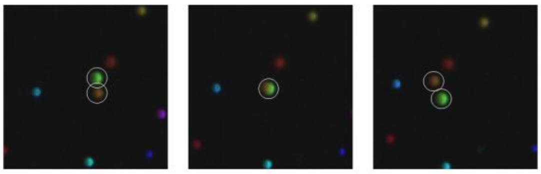


Figure 2. Sample picture of particle overlapping.

Therefore, the tracked particle is allowed to be lost for up to two time steps. The position of the temporarily lost particle is predicted until the next time step, where it is linked as the same particle if the corresponding particle is present at the next time step. Furthermore, the position at the lost time step is linearly compensated by the information from the previous and next positions. This process significantly improves the tracking rate and number of continuous tracking time steps.

EXPERIMENTAL SET-UP

Figure 3 presents the schematics of the experimental setup. The coordinates in the figure are defined as follows: x is horizontal, y is vertical, and z is the depth direction in the camera view field.

A VPL-HW60 LCD projector (Sony) was used as the light source to output the color pattern: it had 1800 lm and 1920 × 1080 pix. The projector provided illumination in the x direction. The image data of color patterns were projected by the projector. A Fresnel lens was set next to the projector to collimate the expanding projection light. The focal length of the Fresnel lens

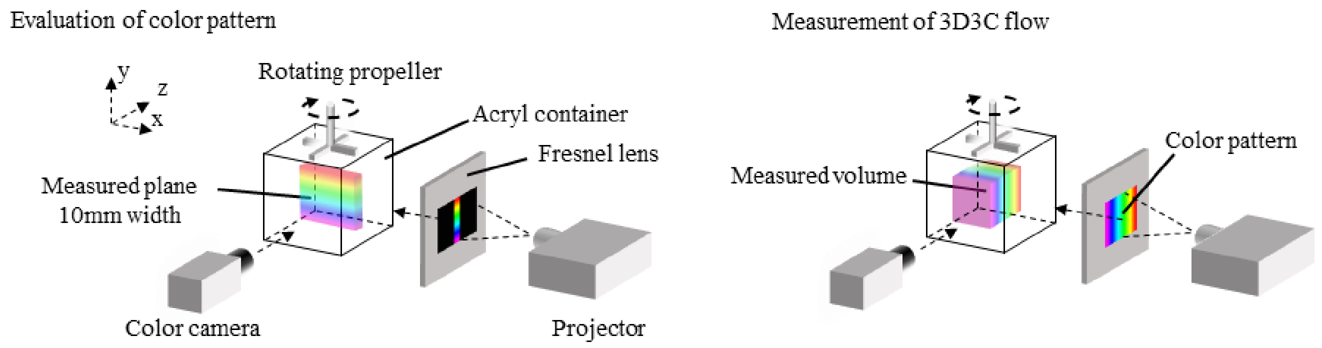


Figure 3. Experimental setup: The left panel shows the schematic of the evaluation test of the color pattern, and the right panel shows the schematic of the 3D3C flow experiment.

was 350 mm, and the illumination width in the z direction was 180 mm.

To increase the color detection accuracy, an AP3200T-PMCL-1 3CMOS camera (JAI) and VS-1218/3CMOS lens (VS Tech) were used in place of a typically used single CMOS color camera. For a single CMOS camera, a Bayer filter having R, G, and B colors with a 1:2:1 ratio covered the CCD/CMOS in an array where cells of the same color did not adjoin each other (Pick and Lehmann, 2009). In contrast, the 3CMOS camera had three CMOS sheets and a dichroic mirror to separate light. Thus, R, G, and B values could be obtained for the same cell of an image sensor array.

An acryl container having inner dimensions of 210 × 210 × 200 mm^3 was filled with particle-suspended water. The tracer particles were Diaion HP20 (Mitsubishi Chemi) with a density of 1.01 $\mathrm{g/cm}^3$, and their diameter was controlled to be 600 to 700 μm through sieving. A rotating propeller with four blades with no elevation angle generated circular flow in the container.

To evaluate the effect of changing color pattern, a calibration curve for converting from color to position was obtained, and the performances of color patterns were compared. To evaluate the accuracy of the depth position determined from different color patterns, the patterns were illuminated as in the left panel of Figure 3. The color changed in the z direction, and the colors and vertical positions of particles were measured simultaneously. The width of the projected image in the z direction was reduced to 10 mm because the field of view changed with depth (z direction).

In the experiment on 3D3C flow measurement, the velocity field of the circular flow was measured as an application test, as shown in the right panel of Figure 3. The color changed in the z direction with particle depth position in the camera view. The sampling rate was 40 fps, and the shutter speed was 1 ms. The distance between the center of the measured volume and the lens of the color camera was 310 mm. The spatial resolution ranged from 71 to 129 μm/pix, changing in the depth (z) direction. The aperture value was approximately 8, and the field depth was enough to capture the particle image in the full depth range.

RESULTS

Figure 4 compares the error histograms of the single-cycle rainbow pattern and the multi-cycle rainbow. Error is defined as the difference between the position determined from the image as the correct value and the position determined from the particle color. The positions are normalized by color pattern width. Introducing the new color pattern clearly enhances the depth resolution. The vertical lines represent the 2.5th and 97.5th percentiles, with the intervals between them representing the 95th percentile widths: 0.032 and 0.020.

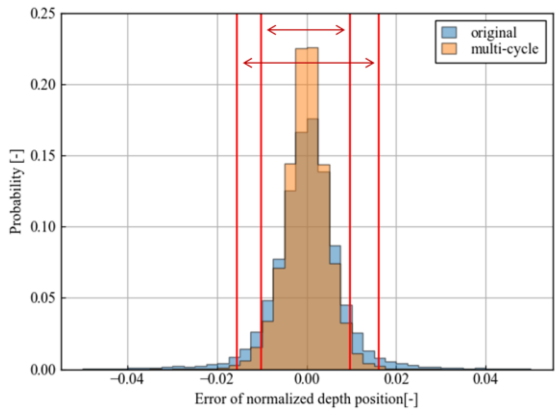


Figure 4. Comparison of the error distributions of two color patterns. Red arrows indicate the 95th percentile widths.

Polynomial fitting is required to obtain the velocity vectors, so particles that are tracked continuously for a certain number of steps are necessary. Figure 5 shows the frequency of successive tracking steps before and after compensation. The data are the results of the 3D3C measurement experiment with a multi-cycle color pattern for 100 time steps. The three figures are the results for different propeller rotation speeds. The greater the amount of movement in one time step is, the more difficult it is to track, but the maximum movements in the three histograms are 15, 45, and 70 pixels from the top.

The process of compensating temporarily lost particles has significantly improved the number of continuous tracking steps, with a reduction in the number of particles with less than 10 continuous tracking steps, which are non-fittable in all velocity ranges.

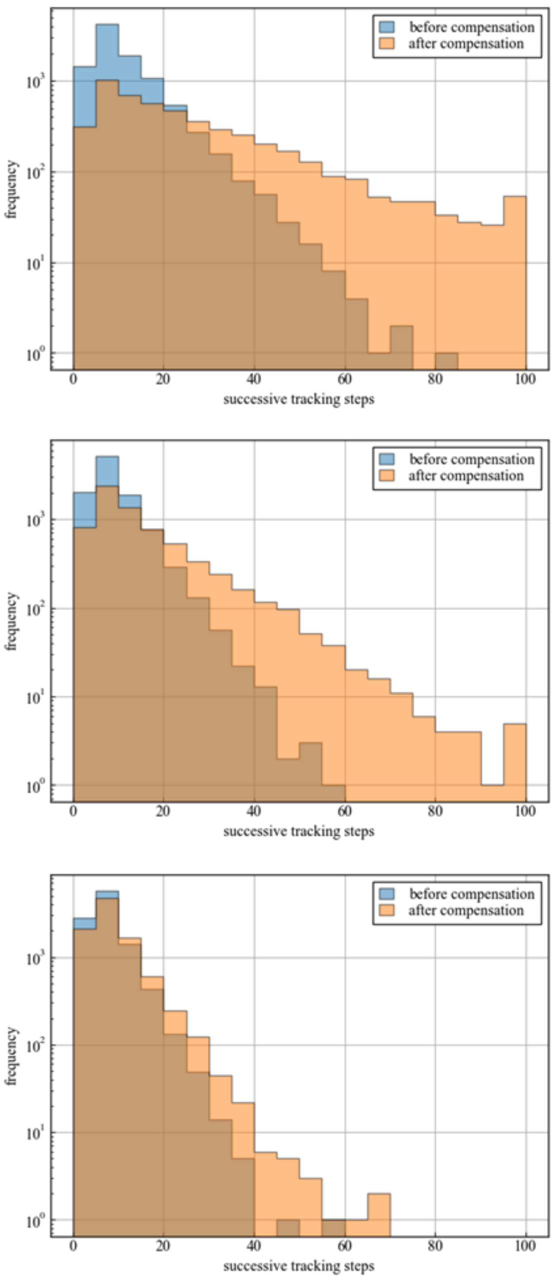
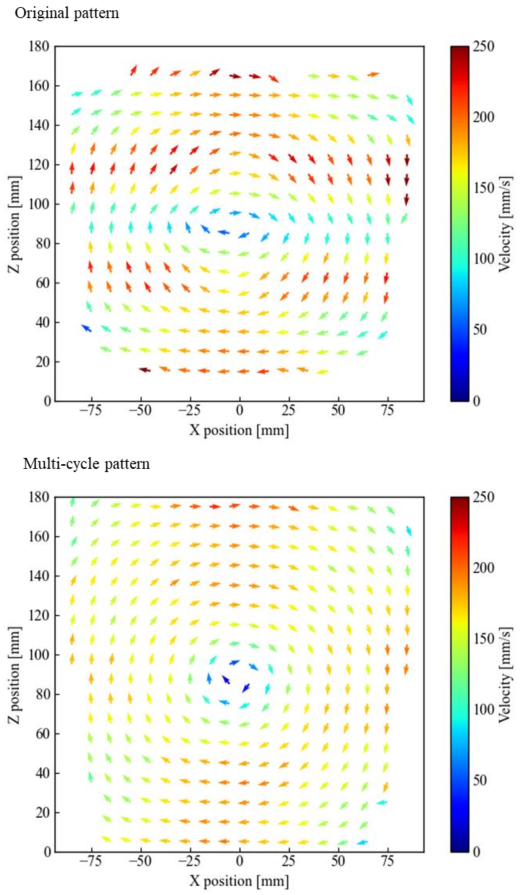


Figure 5. Histogram of successive tracking time steps before and after compensation of lost particles for several velocity fields.

Figure 6 shows the averaged velocity field in the y section measured with two color patterns. The velocities are averaged for each 10 × 10 × 10 mm^3 voxel over the time for 100 steps, and then located on grids. The velocity in the depth direction is measured with sufficient accuracy to determine the overall flow.

In the original rainbow pattern, the flow-like ellipse is measured and fluctuations in the z component are visible. This is a result of the presence of areas with lower position estimation accuracy depending on the depth, i.e. color.

However, a multi-cycle rainbow pattern allows circular motions to be measured clearly with an improved degree of measurement of the z position.


Original pattern

Multi-cycle pattern

Figure 6. Averaged velocity field with two color patterns.

CONCLUSION

In this paper, two new ideas were described and applied to 3D3C rainbow PTV. First, a multi-cycle rainbow pattern was designed instead of the original rainbow pattern. Using more color spaces improved the accuracy of depth determination. This improved the 95th percentile width of error from 0.032 to 0.02 and mitigated the occurrence of partially large error areas in z. Second, tracking was carried out in a raw picture instead of three-dimensional space. Tracking rates were improved by tracking a particle with accurate x and y positions and using color information as an aid. Moreover, for up to two time steps, the tracked particle was allowed to be lost and compensated using the information from the previous and next positions. This process significantly improved the tracking rate and number of continuous tracking time steps.

3D3C circular flow was measured in an application test. The number of successive tracking time steps was significantly improved in all three velocity ranges. Improvement in velocity vector accuracy was confirmed with the averaged circular velocity field.

REFERENCES

Aguirre-Pablo, A. A., Aljedaani, A. B., Xiong, J., Idoughi, R., Heidrich, W., and Thoroddsen, S. T., 2019, “Single-Camera 3D PTV Using Particle Intensities and Structured Light”, *Experiments in Fluids*, Vol. 60, pp. 1–13.

Casey, T. A., Sakakibara, J., and Thoroddsen, S. T., 2013, “Scanning Tomographic Particle Image Velocimetry Applied to a Turbulent Jet”, *Physics of Fluids*, Vol. 25(2).

Noto, D., Tasaka, Y., and Murai, Y., 2021, “In Situ Color-to-Depth Calibration: Toward Practical Three-Dimensional Color Particle Tracking Velocimetry”, *Experiments in Fluids*, Vol. 62, pp. 1–13.

Noto, D., Tasaka, Y., and Murai, Y., 2023, “Low-Cost 3D Color Particle Tracking Velocimetry: Application to Thermal Turbulence in Water”, *Experiments in Fluids*, Vol. 64, pp. 92.

Pick, S., and Lehmann, F. O, 2009, “Stereoscopic PIV on Multiple Color-Coded Light Sheets and Its Application to Axial Flow in Flapping Robotic Insect Wings”, *Experiments in Fluids*, Vol. 47, pp. 1009–23.

Schanz, D., Gesemann, S., and Schröder, A., 2016, “Shake-The-Box: Lagrangian Particle Tracking at High Particle Image Densities”, *Experiments in Fluids*, Vol. 57, pp. 1–27.

Watamura, T., Tasaka, Y., and Murai, Y., 2013, “LCD-Projector-Based 3D Color PTV”, *Experimental Thermal and Fluid Science*, Vol. 47, pp. 68–80.