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A MULTI-COLOR TECHNIQUE FOR THREE-DIMENSIONAL FLOW CHARACTERIZATION

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Abstract—Turbulent flows are fundamentally three-dimensional. Due to their inherent complexity, turbulent flow characterization is heavily relies on experimental research. A multi-color grid technique was recently proposed by the authors as a novel method for characterizing and measuring three-dimensional flows.

In this paper, further improvements of this technique are reported by implementing a new method based on color permutations. Several new advances in the experimental implementation and analysis algorithm are then presented and detailed. Results are presented using color streak images and three-dimensional particle trajectories.

Keywords: 3D; flow visualization; multi-color; flow measurement;

I. INTRODUCTION

Turbulent flows are one of the fundamental topics of classical fluid mechanics. A majority of practical engineering systems encounter turbulent flows, including the wake of buildings and flows in pumps, turbines, and heat exchangers. In these systems turbulence manifests as either a desirable trait, such as enhanced heat transfer, or non-desirable trait, such as dynamic loading on buildings. Complex three-dimensional motion and non-linear dissipative processes, two defining characteristics of turbulent flows make them extremely difficult to study numerically. This makes experimentation the primary means of turbulence research. However, this presents the challenge of developing a technique to measure all three velocity components simultaneously as all components are needed to fully define key quantities in the turbulent kinetic energy budget.

Numerous techniques have been developed in the past to measure flow velocity while few have been used quite often for turbulent flow measurement. Hot-wire anemometry is one of the simplest techniques where velocity is determined from flow passing over a very thin heated wire attached to a probe. By deploying several probes at orthogonal angles, three-dimensional velocity can be determined. This technique has the benefit of excellent temporal resolution but lacks the ability to capture the flow field with good spatial resolution. Furthermore, the probe array intrudes upon the flow. Planar Particle Image Velocimetry (PIV) is a non-intrusive technique that generates a two-dimensional flow field by taking images of a laser-illuminated seeded flow. This produces a flow field with high spatial resolution but is limited to planar measurements. Stereoscopic PIV builds upon this by utilizing two off-axis cameras viewing the light sheet [1]. From the captured images, a 3D flow field is constructed; however, the out-of-plane velocity has been shown to have questionable accuracy and no out-of-plane gradients can be determined [2,3]. Tomographic PIV is a further advancement of the PIV technique where four or more cameras observe an illuminated volume [4]. By applying a computational scheme to the images of the seeded flow, all three velocity components can be estimated. It has been shown that the calculated third velocity component is of questionable accuracy, especially in high shear flows, due to ambiguities in identifying seed particles, called ghost particles [5,6].

Recently, wavelength-encoding techniques have been developed to measure flow velocity. Rainbow Volumic Velocimetry (RVV) is one such technique where one camera views a seeded flow passing through a volume illuminated with the polychromatic light spectrum [7]. In this method, two velocity components are found from tracking particles while the third is derived from color changes corresponding to the particles' motion in the direction normal to the cameras viewing plane. This technique produces a three-dimensional flow field but is restricted to small volumes as the out-of-plane velocity components accuracy is strongly dependent upon of the width of each color in the volume [7]. A new method of volumetric color illumination was recently proposed by the present authors utilizing a grid pattern [8]. In this grid-based technique, color changes occur over multiple planes with respect to the camera viewing plane. With many colors and permutations of those colors, high spatial resolution in the out-of-plane direction is possible. The initial implementation of this grid-based technique was able to resolve three-dimensional motion while simultaneously identifying challenges.

In this study, the limitations of the grid-based technique are presented along with progress on a series of advances both in experimental implementation and in analysis algorithm design. Findings of the grid-based technique are first reviewed and weaknesses are identified. Then, recent progress on improvements are presented with a refined experimental method and analysis algorithm leading to a newly developed technique. The new technique is then tested and 3D particle trajectory results are presented.

II. Review of the Multi-color Grid Technique

The multi-color grid technique for flow characterization divides the measurement volume intro an N × N grid where N colors are used [8]. The color pattern is designed such that each color appears only once in each row and column. Hence when a particle is observed to change color without a corresponding pixel shift in the camera view plane, it can be concluded the particle moved perpendicular to the camera view plane. Similarly, the particle would change color in addition to a pixel shift if the motion is parallel to the camera view plane. One of the advantages of the grid technique is that the number of permutations of colors, exceeds the number of colors enabling the grid pattern to be extended. This allows for improved spatial resolution in the out-of-plane direction.

The multi-color grid technique was implemented using a simple experiment of tracking particle motion underwater using a three-color grid and a basic analysis procedure [8]. Captured streaks were discretized with a simple streak technique that was able to capture many points along each streak allowing for the general shape to be well-resolved. The three-dimensional position of the streak was found using linear interpolation of color described with hue from the Hue-Saturation-Value (HSV) color model. This demonstrated that a grid technique was able to capture basic three-dimensional motion [8].

The three-color grid pattern used only contained red, green, and blue however resulted showed other colors such as pink were present [8]. This is due to neighboring colors interfering with each other. When this technique was implemented with a six-color grid, this color cross-talk effect was stronger and began to interfere with three-dimensional position determination. Hence, increasing the number of colors, thus reducing grid size, is a major obstacle in improving the possible spatial resolution of the technique due to cross-talk between neighboring colors.

The LCD projector used in experiments produced a highly divergent beam, resulting in a rectangular frustum shaped measurement volume. The calibration of the measurement volume was very simple based on a hue threshold [8]. The basic streak discretization technique had issues in accurately capturing the ends of streaks and could not handle streaks with high curvature.

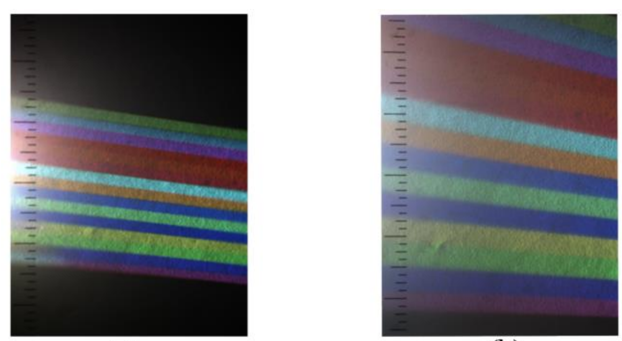
III. Developing the Color Permutation Method

Several advancements and improvements have been completed to address these limitations and to refine the technique. The first improvement is in the light beam delivery to overcome the beam divergence issue. This was achieved by placing a planoconvex lens in front of the LCD projector. This has the effect of producing an easily modelled measurement volume in the shape of a parallelepiped. This improvement to reduce beam divergence is illustrated in Fig. 1 where the new approach is compared with the lens-free case. From observing the thickness of each colored region in the image, it is clear that the lens significantly reduces the beam divergence improving the spatial uniformity of each single-colored region.

A new calibration technique has been developed for more robust analysis. The new method fits a normal distribution to hue values using the HSV model from a single-colored volume. The region within three standard deviations of the mean hue is defined as the “core” and the region beyond this is defined as the “boundary”. An example of the core and boundary regions for a three-colored volume identified by the technique are shown in Fig. 2. Each core region is now separated by two boundary regions..

The previous streak discretization method would have issues near ends of streaks where points were mis-aligned and could not handle streaks with significant curvature. These issues have been overcome with a new discretization technique that follows the shape of a streak. In this approach, a given streak is divided into many streak subdivisions. Each subdivision is identified by a white region where segmented streak and semi-circle intersect, as shown in Fig. 3. The centroid of the subdivision, as marked by the red asterisk, and the median hue are stored for each subdivision.

The issue of cross-talk between colors has been addressed by defining the mid-plane between neighboring single-colored volumes. This leads to the case where if a particle appears as an undefined hue in the whole measurement volume, it must exist between neighboring volumes. By identifying the volumes where the particle was last found before and after transition, it is possible to determine which mid-plane the particle passed through. This approach is dependent upon proper identification of volumes before and after transition.



(a) (b)

Figure 1. Comparison of illuminated volume (a) with planoconvex lens and (b) without lens showing the effect of the lens on beam divergence.

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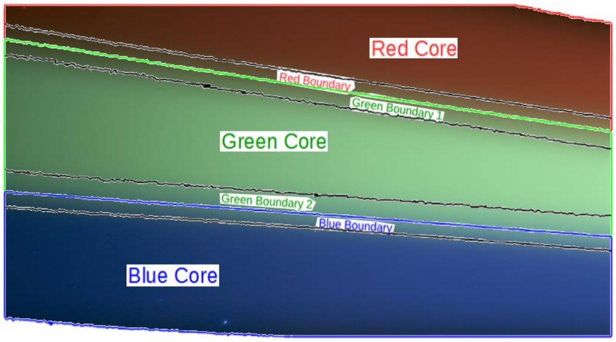

Figure 2. Cross-section of three-color grid pattern using the new calibration technique. The core and boundary regions for each color are outlined and labeled.

The robustness of volume identification and spatial resolution in the out-of-plane direction can be greatly improved via color permutations. For a selection of N colors, they can be arranged such that each color neighbors every other color only once. This allows for each color to appear several times in the volume where each appearance features unique neighbors. The result of this configuration is that once a particle changes color, e.g. a sufficiently long streak is captured by the camera, the three-dimensional position is known. As colors can repeat in the volume and mid-planes between colors are defined, this leads to a substantial increase in spatial resolution compared to the previous method for the same number of colors.

The culmination of these improvements have led to the color permutation method where color permutations drive the resolving of motion in the third dimension. For planar motion in the camera's field of view, the resolution provided by pixels far surpasses what is offered by the grid pattern. Hence, color changes are only needed in the out-of-plane direction. Moreover, this simplifies analysis as color cross-talk is limited to one direction.

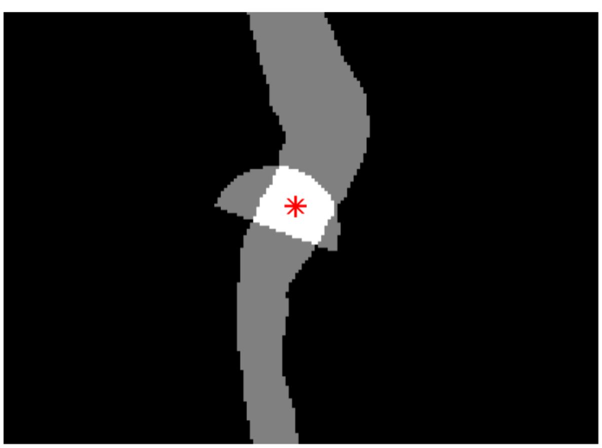

Figure 3. One step in the process of streak discretization. The subdivision is the white intersection area between semi-circle and segmented streak. The red asterisk denotes the subdivision centroid.

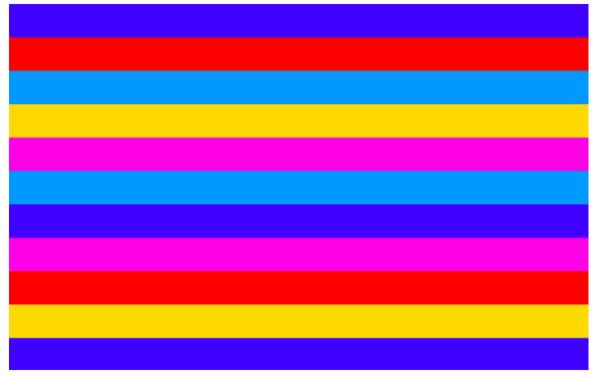

Figure 4. Five-color pattern with permutations to produce 11 layers used in experiments.

IV. Results

The color permutation technique was tested using a five-color permutation pattern as shown in Fig. 4. This image contains one of many possible permutations of five colors. There are 11 single-colored volumes and by utilizing mid-planes, this gives 21 possible out-of-camera-plane positions, over 4 times larger than the 5 positions possible with the previous technique. The experimental setup and conditions were the same as those previously reported [8].

Fig. 5a shows a two-frame composite image of a particle traveling from left to right. The corresponding two-dimensional discretized streak is shown in Fig. 5b. Comparing the discretized streak to the original image shows the new path-following discretization method successfully captures local curvatures in the streak. This is evidenced by features such as the drop in Z position where $Y \approx 1200$ pixels, matching the left-most orange part of the streak composite image. Similar features along the streak image are well captured by the new discretization technique. There were no mis-aligned points at the ends of each streak showing the new technique has improved over the previous method in this aspect.

Fig. 6 shows the discretized streaks in three dimensions describing the particle trajectory. The left-most part of the streak at $Y \approx 900$ pixels was found to be in layer 11, then continuing along the streak showed the streak moving three-dimensionally up to layer 6. At this point, the second frame in the composite image begins where the streak continues from $Y \approx 1700$ pixels and layer 6 up to $X \approx 2500$ pixels in layer 3. The additional depth positions obtained by color permutations and mid-planes showed good resolution of the particle's motion in the out-of-camera-plane direction.

V. Analysis of New Findings

Numerous changes have been made to the multi-color grid flow visualization technique. A planoconvex lens placed in-front of the projector greatly reduces beam divergence.

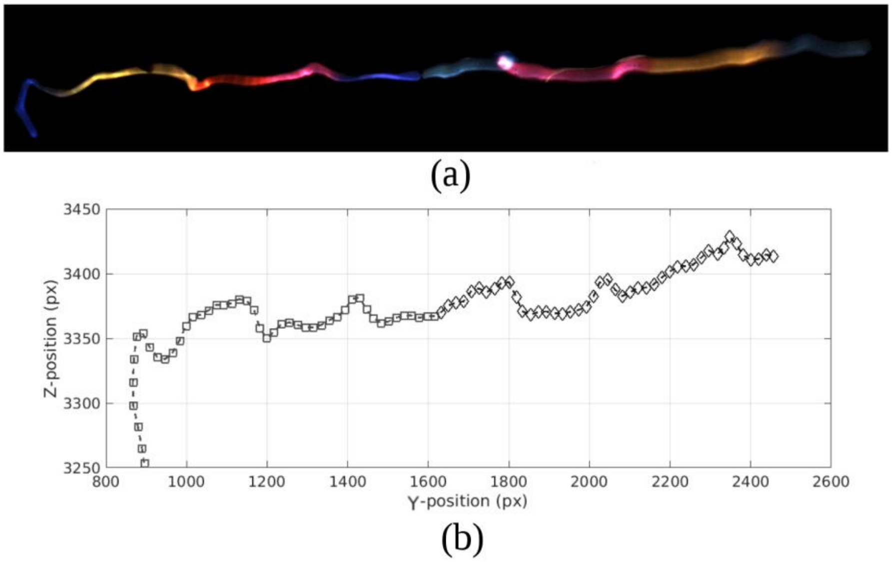

Figure 5. Two-frame composite image (a) of streak captured and two-dimensional view of discretized streak (b). The image has been rotated to match the coordinate system of the plot

This changed the shape of the illuminated volume from a rectangular frustum to a parallelepiped which is very simple to describe mathematically. Furthermore the size of each single-colored volume is smaller compared to the divergent beam setup, providing an increase in spatial resolution in one direction. With precise alignment of the planoconvex lens, a rectangular prism shaped volume is possible.

The two analysis algorithm changes, improved calibration and discretization, lay the ground work for high quality flow characterization. In the new calibration technique, using a normal distribution to define the hue threshold enables the technique to be implemented with many different projectors and clearly defines the calibration core and boundary regions. The new discretization technique demonstrated an ability to follow the shape of a streak with somewhat complex geometry, such as local curvatures that characterizes the three-dimensionality of the flow. These advancements provide an opportunity for the future growth of the analysis algorithm.

The addition of mid-planes and color permutations together provided a very significant increase in out-of-camera-plane spatial resolution. The introduction of mid-planes mitigated the effects of cross-talk between neighboring volumes as hues not defined by the grid pattern do not need to be explicitly determined. Mid-planes also increased the out-of-plane resolution by a factor of just under two.

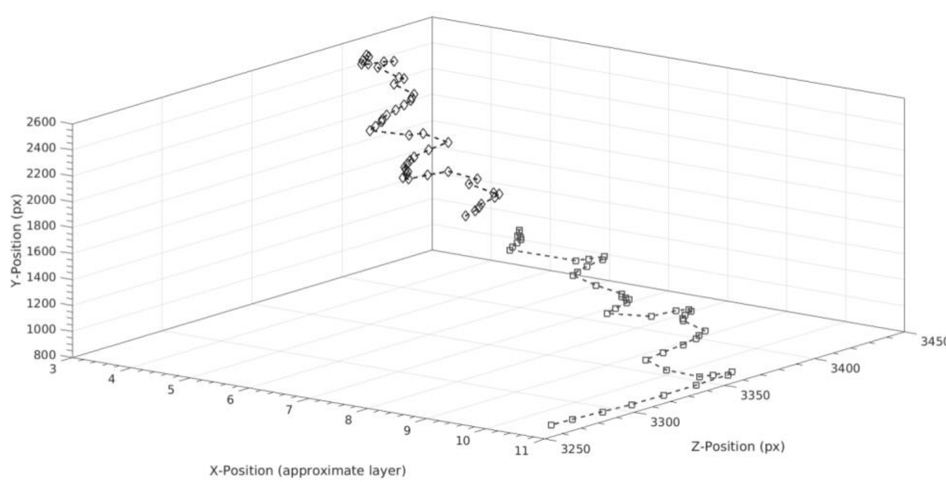

Figure 6. Three-dimensional reconstructed particle path corresponding to the two-dimensional discretized streak in Fig. 5.

Color permutations demonstrate that a large increase in spatial resolution is possible with only a few colors via permutations. As tested in the present study, 5 colors were able to produce 11 different core depth positions and with mid-planes, generated 21 possible positions. The cost for this improvement is loss of color uniqueness in the volume as a red region could end up in two different positions. This is an ambiguity that cannot be resolved until the streak changes color.

This color permutation method has shown strong potential for future growth. With additional colors, more permutations are possible, producing further improvements in out-of-plane spatial resolution. Work is currently in progress in this area of identifying valid color permutations for six or more colors.

Thus far the color permutation method has presented results from the 3D path traversed by a single particle. While this is useful to build a framework and test analysis methods in isolation, it is not practical. Multiple particles must be present for meaningful flow characterization. In a test where many particles are present, the streaks left behind by their motion may overlap or otherwise interact. Current work is focused on implementing analysis methods for cases where streaks interact.

Finally, the three-dimensional reconstruction work has been performed manually to date. Currently an automatic reconstruction technique is in development to convert hue data along streaks into depth positions. There is also on-going work in more robust preprocessing methods to better separate streaks from background noise and select streaks with color changes to ensure compatibility with the color permutation method.

VI. Conclusion

In conclusion, the multi-color grid technique was successful at resolving 3D particle motion but did reveal many flaws in the method and early implementation. The present paper serves as a progress update that identifies and resolves these limitations while advancing the technique utilizing color permutations and improved algorithm design. There are new challenges found in the updated method that join unresolved issues. Presently, work continues on addressing these issues and further refining the technique. These findings using the color permutation method will drive future research and development on this technique.

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