

Research on three-dimensional flow field measurement in a microchannel using a single-lens dual-camera imaging system

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ABSTRACT

Accurate three-dimensional (3D) flow field measurement in microchannels is crucial to understanding the complex transmission phenomena in droplet-based microfluid systems. This research uses a single-lens dual-camera imaging system based on the principle of out-of-focus ranging (depth from defocus), which can realize the accurate three-dimensional positioning of fluorescent tracer particles and reconstruct the internal flow field of droplets. The system adopts a telecentric industrial lens and a beam splitter to effectively eliminated the issue of inaccurate positioning in defocused images by capturing two out-of-focus images of the same particle under different focal length offsets. In addition, the dual-camera image fusion model based on convolutional neural network (CNN) realizes the three-dimensional positioning of particles by learning the positional relationship between the image characteristics and depth of out-of-focus particles. The model is good at particle depth prediction, and the error range is controlled within $\pm 10\%$. At the same time, the three-dimensional reconstruction of the droplet flow field in the rectangular microchannel is realized in combination with depth information and particle tracking speed measurement technology (PTV). The experimental results reveal the significant shear-induced circulation and internal recirculation mode near the droplet interface, and explain the droplet movement characteristics in the restricted microchannel.

1. Introduction

Microfluidic droplet systems are widely used in chemical synthesis, biomedical analysis, and microscale heat transfer. Accurate measurement of three-dimensional flow structures inside droplets is important for understanding mass transfer, mixing behavior, and interfacial dynamics in confined microchannels (Hou et al., 2025; Yadav et al., 2025; Teja et al., 2025).

Traditional microchannel flow measurements are mainly based on two-dimensional particle image velocimetry (PIV), which cannot fully capture complex three-dimensional flow structures (Carneiro et al., 2023; Yang et al., 2025). Existing 3D measurement approaches, including confocal microscopy and digital holography (Jun et al., 2016; Li et al., 2016), can provide depth information

but usually require complicated optical arrangements and expensive computational reconstruction.

Depth-from-defocus (DFD) techniques provide an alternative approach by estimating particle depth directly from defocused image features. Compared with scanning-based methods, DFD systems are simpler and more suitable for confined microfluidic environments (Barnkob & Rossi, 2020; Zhou et al., 2021). However, conventional single-camera defocus imaging suffers from depth ambiguity near the focal plane because particles located before and after focus may produce similar blur patterns.

To address this limitation, this work develops a single-lens dual-camera imaging system capable of simultaneously capturing two defocused images of the same particle. A CNN-based image fusion model is further introduced to establish the relationship between dual-view particle features and particle depth. Finally, the reconstructed particle positions are combined with PTV to obtain the 3D velocity field inside moving droplets.

2 Experimental Method

Figure. 1 shows the single-lens dual-camera setup. Fluorescent particles in the microchannel are illuminated by a 532 nm laser. A 10× microscope objective and a beam splitter direct light to two cameras (Imaging DFK 33UX273). A 2 mm spacer between camera 2 and the beam splitter creates different defocus degrees. The telecentric lens avoids parallax issues. The focal plane ($z=0$) is defined by the sharpest particle image using the Tenengrad method. Depth calibration is performed by translating particles with a piezo stage ($1\ \mu\text{m}$ step) from $-50\ \mu\text{m}$ to $+50\ \mu\text{m}$.

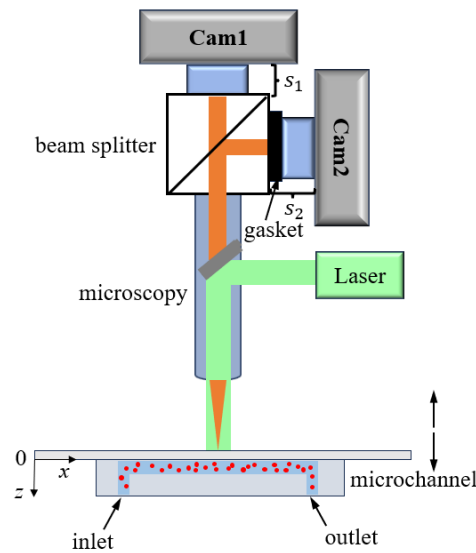


Figure. 1 Single-lens two-camera measurement system with coaxial laser illumination (the difference in distance between these two cameras and the beam splitter $\Delta s=2\text{mm}$).

A convolutional neural network (Figure. 2) takes paired particle images (64×64 pixels each) from both cameras as dual-channel input. The network comprises two convolutional layers with ReLU and max pooling, followed by a fully connected regression layer. Training uses ground truth depths from the piezo stage. The loss function is mean squared error (MSE) between predicted and true depth. The model is implemented in PyTorch with an NVIDIA RTX 3060 Ti GPU.

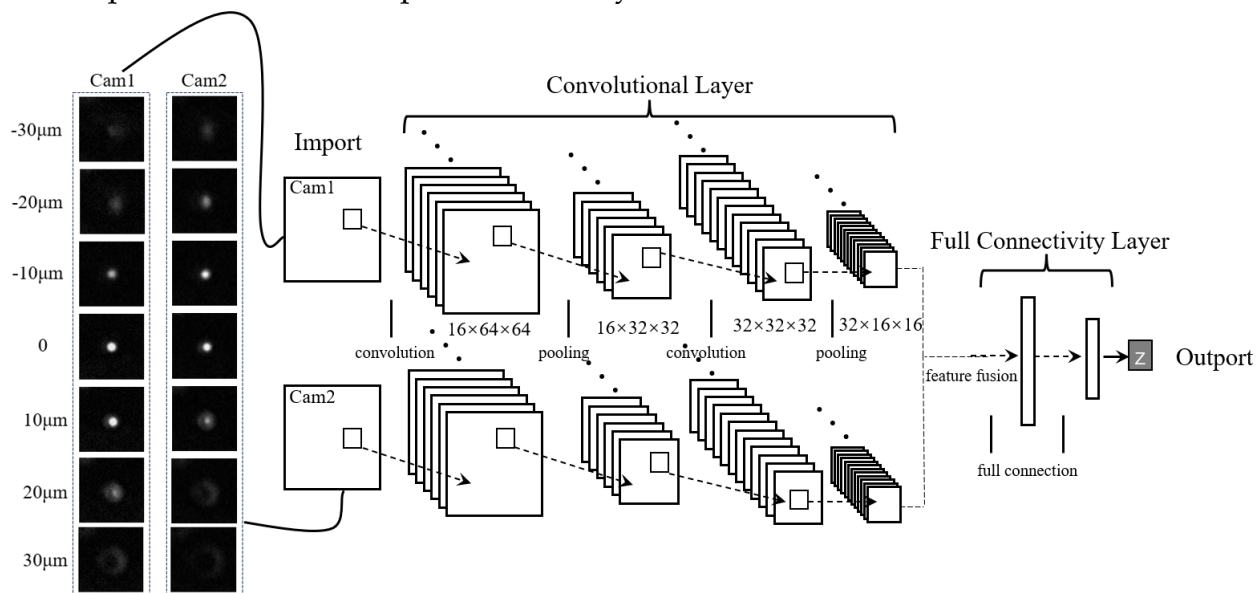
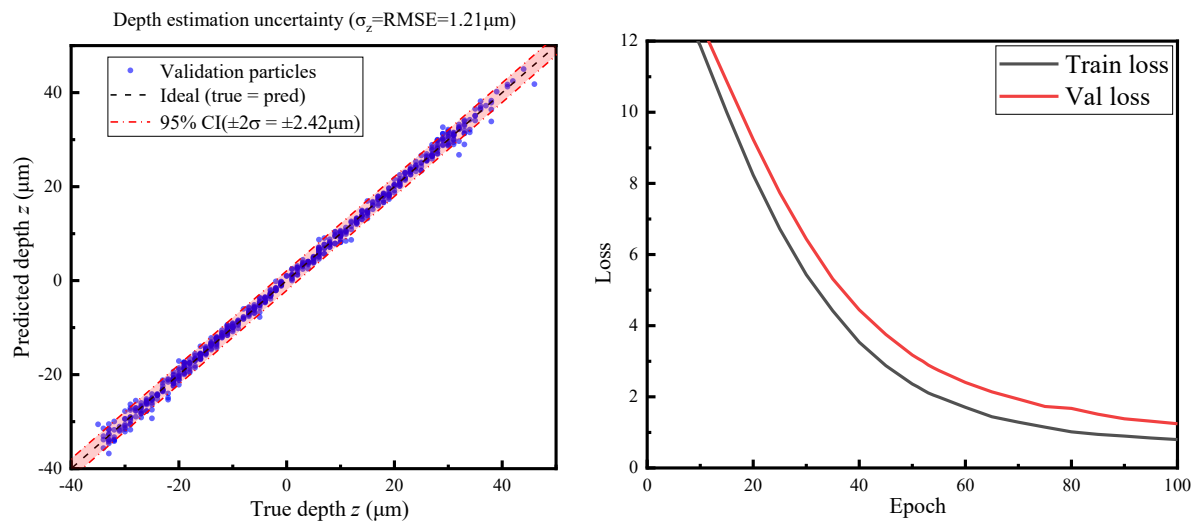


Figure. 2 Deep training model for two-camera image feature fusion based on convolutional neural network. After depth prediction, the 3D coordinates of fluorescent particles are obtained (x , y from image plane, z from CNN). Particle tracking velocimetry (PTV) matches particles between consecutive frames ($\Delta t = 12.5$ ms, FPS=80) using spatial proximity and motion continuity. Instantaneous velocity is computed as $V = \Delta r / \Delta t$. The 3D velocity field inside droplets is reconstructed.

3 Results and Discussion

Figure. 3(a) shows predicted vs. true depth for test data. Scatter points closely follow $y=x$, with R^2 near 1. The error is within $\pm 10\%$. The training and validation loss curves (Figure. 3b) converge steadily without overfitting, demonstrating good generalization.



(a) Quantitative validation of depth estimation based on CNN. (b) The relationship between epoch and loss.

Figure. 3 Depth prediction model accuracy and training loss curves.

Droplets are generated in a flow-focusing microchannel (main channel 200 μ m wide, 50 μ m deep). Continuous phase: silicone oil; dispersed phase: 60% glycerol/40% water. Figure. 4 shows dual-camera images of fluorescent particles inside a moving droplet at $t=0$, 0.5 s, and 1 s, along with reconstructed 3D positions. The same particle appears in red, green, and blue across times, revealing its trajectory.

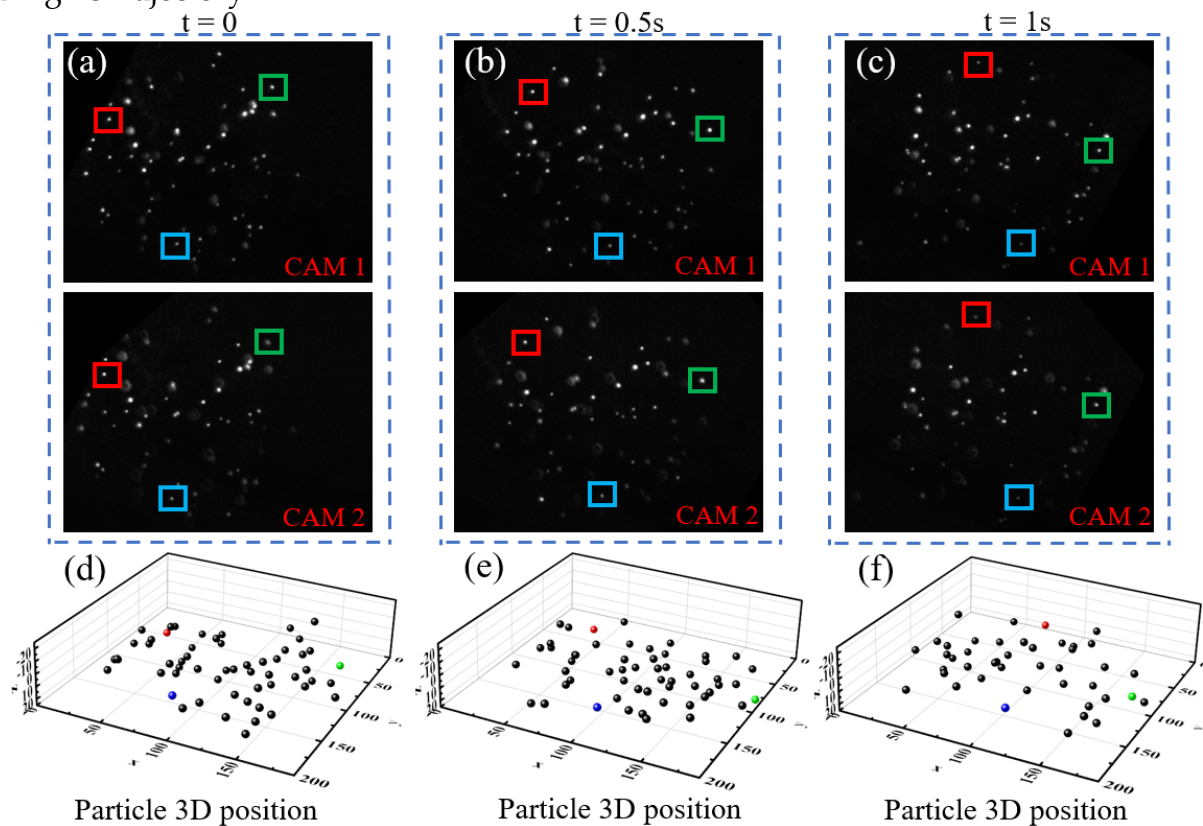


Fig. 4 Three-dimensional position of fluorescent particles within a moving droplet.

Figure. 5 presents the 3D velocity vector field inside the droplet. Higher velocities appear near the droplet interface due to shear from the continuous phase. Internal recirculation is observed in the central region. Projections onto xy and xz planes (Figs. 5b,c) further illustrate the circulation structure. These results confirm that the proposed method captures complex 3D flow features in confined microchannels.

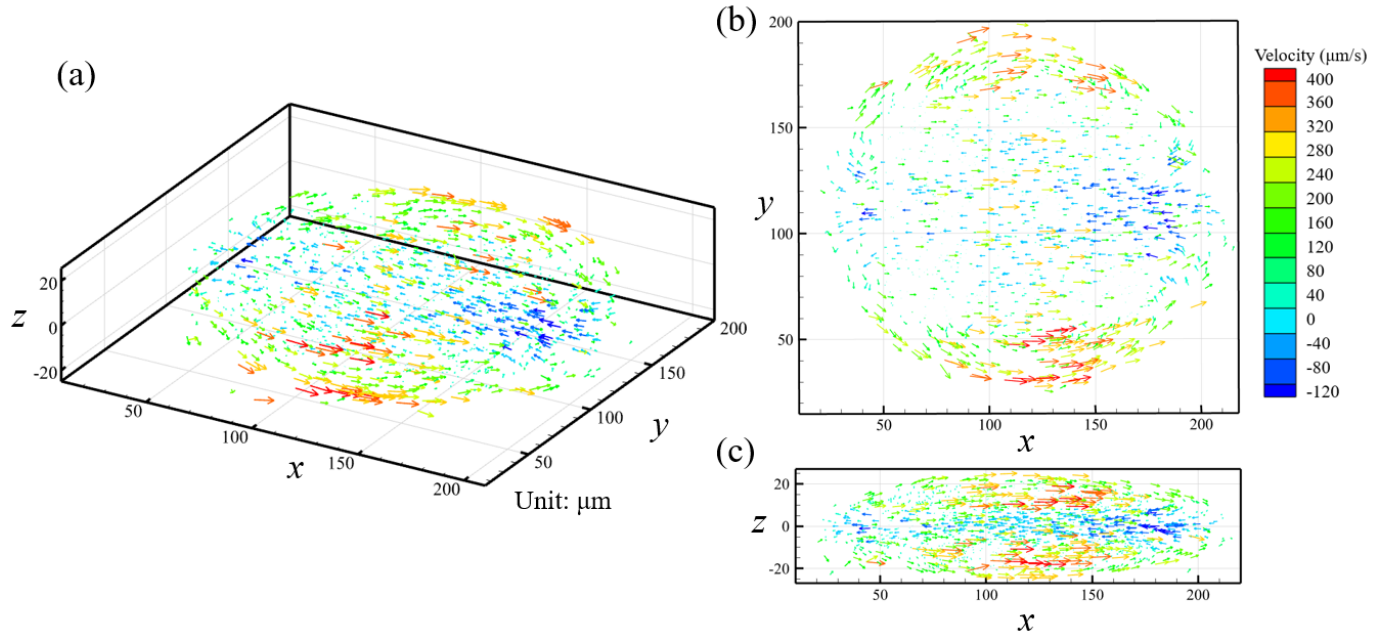


Figure. 5 (a) Three-dimensional velocity vectors within a moving droplet in a rectangular microchannel. (b) Vector diagram of velocity in xy -plane. (c) Vector diagram of velocity in xz -plane.

4 Conclusions

A single-lens dual-camera DFD system with CNN-based depth prediction has been developed for 3D flow measurement in microchannels. Key conclusions:

- (1) Dual-camera imaging eliminates defocus ambiguity, improving depth localization accuracy.
- (2) The CNN model predicts particle depth with error within $\pm 10\%$ using fused dual-camera features.
- (3) Combined with PTV, the method successfully reconstructs 3D velocity fields inside moving droplets.
- (4) Results reveal shear-induced circulation at the droplet interface and internal recirculation, validating the system for microscale 3D flow studies.

Future work will focus on higher-precision models and comparison with numerical simulations.

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