Holographic Particle Velocimetry via Gaussian-Parameterized Particles

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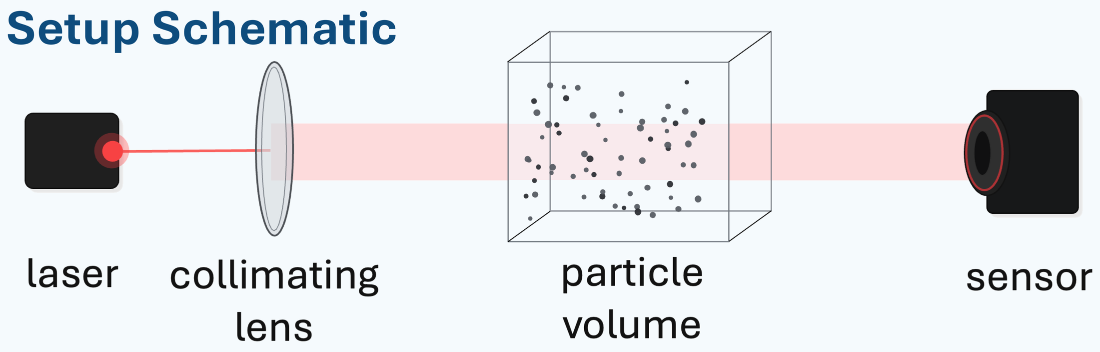
Continuous 3D Gaussian particles improve localization and enable joint flow reconstruction.

Introduction

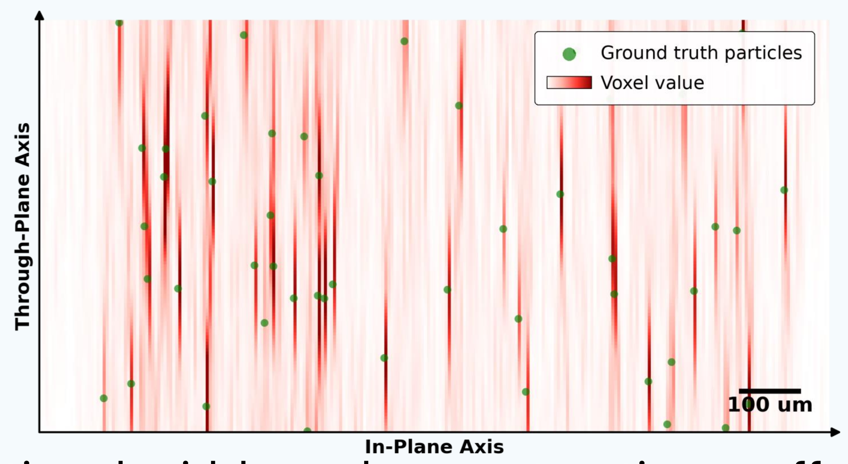
Holographic particle image velocimetry (HPIV) uses digital inline holography to recover 3D particle motion from 2D intensity measurements[1]. A collimated laser illuminates the particle volume, and a camera records the transmitted interference pattern, or hologram.

Experiment Setup Schematic



The hologram can be digitally backpropagated to different axial planes to localize particles in 3D[2]. Recording a hologram sequence and tracking the reconstructed particles over time enables volumetric flow estimation[3].

Representative slice



Challenge Conventional grid-based reconstructions suffer from poor axial resolution and artifacts[4], limiting accurate particle localization and subsequent flow estimation.

Method: Gaussian Particles

Represent particles directly as continuous 3D Gaussians instead of reconstructing a voxelized volume.
Particle positions are continuous parameters, enabling sub-grid localization while enforcing a compact particle model.

$$G_i(x,y,z) = a \cdot \exp\left(-\frac{\|(x,y,z)-\mu_i\|^2}{2r^2}\right)$$

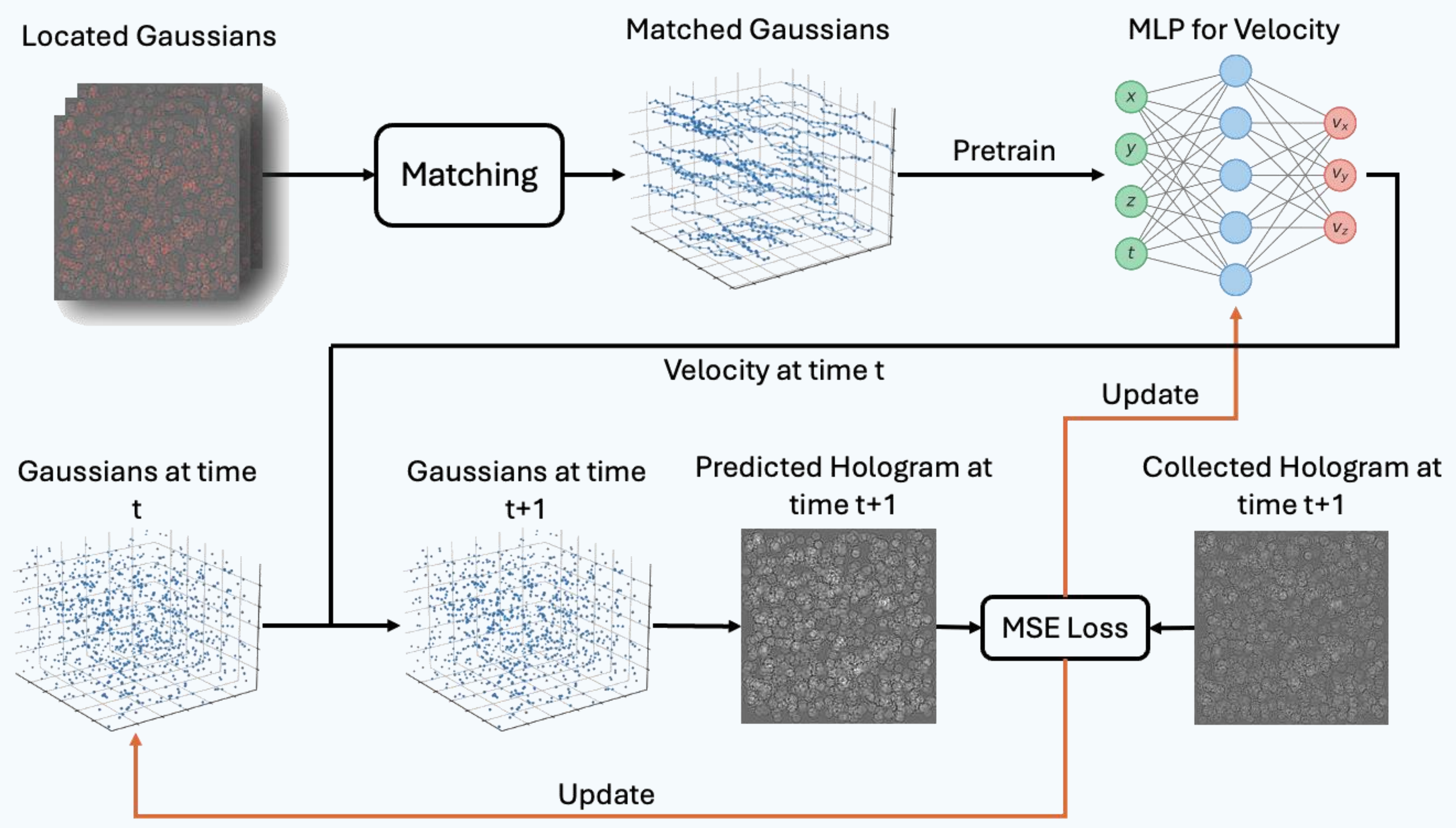
- Each particle G_i : position $\mu_i \in \mathbb{R}^3$, radius r_i, amplitude a_i

Particle localization pipeline:

Initialize Gaussians → Forward render → Optimize μ, a → Prune low-a → Localized particles

Method: Neural Flow Field

A coordinate-based MLP maps particle position and time to velocity, enabling joint optimization of particle positions and the flow field.

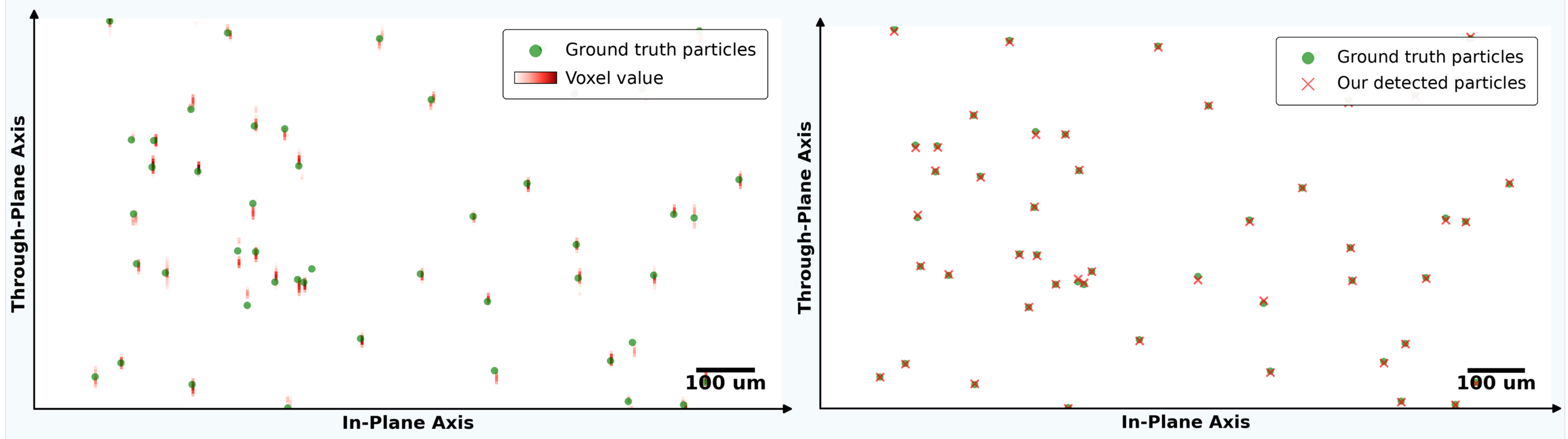


- Input: particle position and frame index (x, y, z, t)
- Output: 3D velocity (v_x, v_y, v_z)
- Training signal: predicted particles at t+1 are forward-rendered and compared with the measured hologram.

Simulation Results

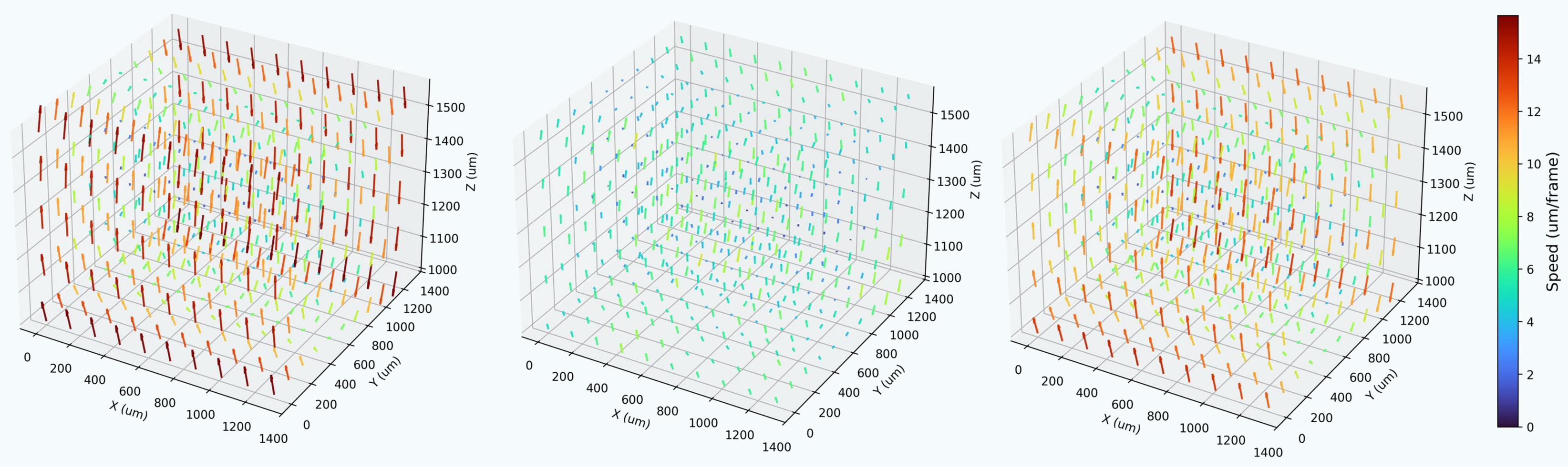
We evaluate our method on simulated vortex-flow data and compare against Holo-Flow[3], a grid-based holographic particle reconstruction baseline.

Representative slice



- Holo-Flow shows axial elongation and localization error; ours closely matches ground truth.
- For single-frame particle reconstruction, our method achieves 99.0% precision and 97.1% recall with a mean 3D localization error of 2.57 μm, compared with 78.3%, 80.6%, and 6.12 μm for HoloFlow.

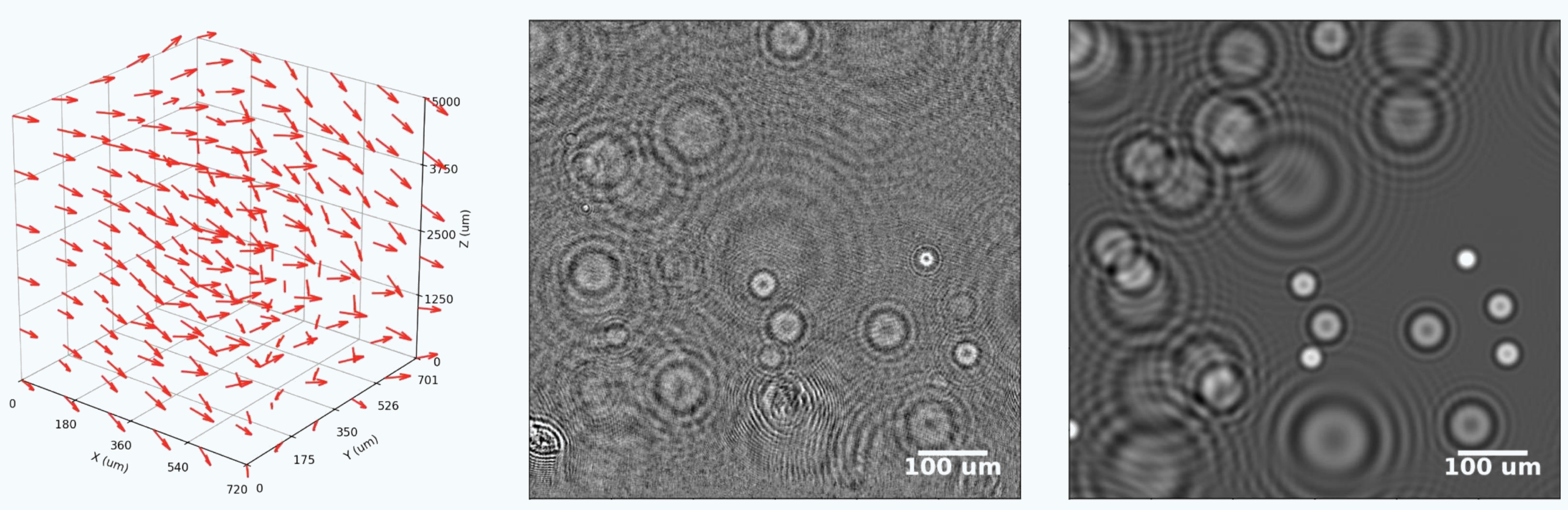
3D velocity-field reconstruction



- Our recovered flow closely matches the ground-truth vortex field with substantially smaller vector error.

Proof-of-Concept Experimental Result

We apply our method to an experimental hologram video of polystyrene beads undergoing Vorticella feeding currents[5].



- The recovered velocity field exhibits a coherent dominant flow direction.
- The forward-rendered hologram closely matches the captured measurement.

Limitation & Future Work

Current limitation: particles at extreme depths are occasionally missed.

Future work: improve localization robustness across the full imaging depth.

Takeaways

Continuous particle representation

- 3D Gaussian particles replace rigid voxel grids, enabling continuous localization.

Joint particle + flow reconstruction

- Particle positions and a neural velocity field are jointly optimized from hologram measurements.

Improved reconstruction

- Simulations show improved localization and flow estimation; experimental data demonstrate physically coherent 3D flow.

Acknowledgements

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Selected references

[1] Meng et al., "Holographic particle image velocimetry: from film to digital recording," Meas. Sci. Technol. (2004).
[2] Kim, "Principles and techniques of digital holographic microscopy," SPIE Rev. (2010).
[3] Chen et al., "Snapshot space–time holographic 3D particle tracking velocimetry," Laser Photonics Rev. (2021).
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[5] Kabuli et al., "Observing Vorticella feeding currents with digital in-line holography particle tracking," COSI (2022).