

Dispersion-based 4D feature learning for waterborne particle monitoring

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Abstract: We propose a compact AI-based 4D feature learning method termed Snapshot HoloSpec for real-time monitoring of waterborne microparticles, achieving a macro F1 of 98.11% and enabling real-time, label-free environmental monitoring.

1. Introduction

The proliferation of pollutants and microparticles in aquatic systems poses a severe and growing threat to the environment and to human health [1]. Many existing detection methods, such as Fourier-transform infrared spectroscopy and Raman spectroscopy, are limited by their high cost, low throughput, and lack of real-time capability [2,3].

To address these challenges, we propose a field-portable, four-dimensional (4D) computational optical imaging system for real-time monitoring of waterborne particles. By integrating digital holography and multispectral imaging, the system enables simultaneous 3D spatial localization and particle classification in a single snapshot. A prism-based dispersive encoder facilitates continuous spectral encoding without sacrificing spatial resolution, enabling single-shot capture of high-resolution 4D features without moving parts or complex masks. Advanced deep learning algorithms decode these dispersion-compressed features, transforming raw optical data into actionable information. This compact, cost-effective system provides a powerful tool for tracking pollution pathways, identifying emission sources, and enabling real-time environmental assessments, offering transformative potential for waterborne particle monitoring.

2. Methods and experiments

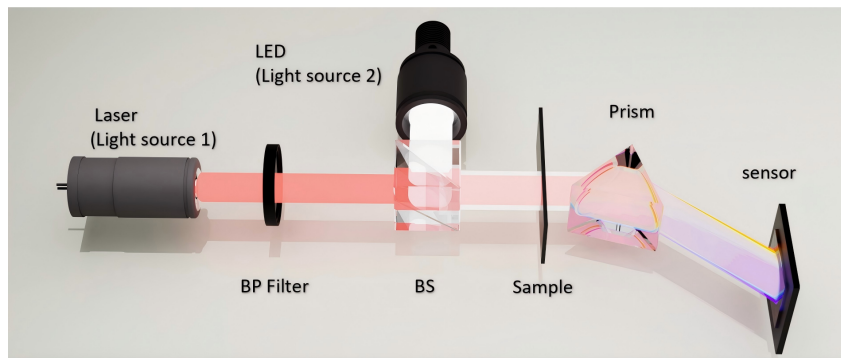


Fig. 1. Setup for 4D optical imaging system.

Our system setup is shown in Fig. 1: two orthogonally aligned light sources, combined using a beam splitter (BS), illuminate the sample. A 532 nm laser provides the in-line holography channel encoding phase information. A broadband white LED adds a spectral dimension, enabling chemical contrast for enhanced classification. The transmitted optical field is angularly dispersed by a prism and recorded as a compressed spatial-spectral distribution on a CMOS sensor.

Experiments used well-labeled samples, including microplastic (MP) films (PMMA, PC, PP, PET, PVC), water fleas, and environmental impurities (gravel, soil, leaf debris). MP films (1–5 mm) represent common aquatic plastics. Water fleas (0.2–5 mm), abundant in freshwater ecosystems, were included to simulate in situ detection due to their size overlap with MPs and impurities. To mitigate white light background effects and ensure consistent

analysis, each frame of our method was linearly normalized to match the brightness and contrast of its paired in-line hologram (Holo), minimizing illumination artifacts. The examples of these images are shown in Fig. 2.

For high-accuracy material identification and discovery, we fine-tuned AlexNet on dispersion-based dataset and Holo dataset to compare the classification performance of six categories (PC, PMMA, PP, PVC, impurities, water fleas). The model was trained for 30 epochs using the Adam optimizer (learning rate 0.001), cross-entropy loss, a batch size of 32, and an 8:2 train-test split with stratified sampling. Inputs were resized to 256×256 pixels and normalized.

3. Results and discussion

To validate the material recognition capability of our system, we trained and tested AlexNet on the dispersion-based dataset and repeated the process on the Holo dataset for comparison. Fig. 3 shows the results, including training loss curves and intra-class distance. Notably, the intra-class Euclidean distances for dispersion-based images are significantly smaller than those for Holo samples, indicating more compact feature representations. The loss curves show rapid convergence within 5 epochs, stabilizing around 0.1, demonstrating effective training. With our system, a macro F1 of 98.11% was achieved, confirming that AlexNet efficiently extracts discriminative features for classification.

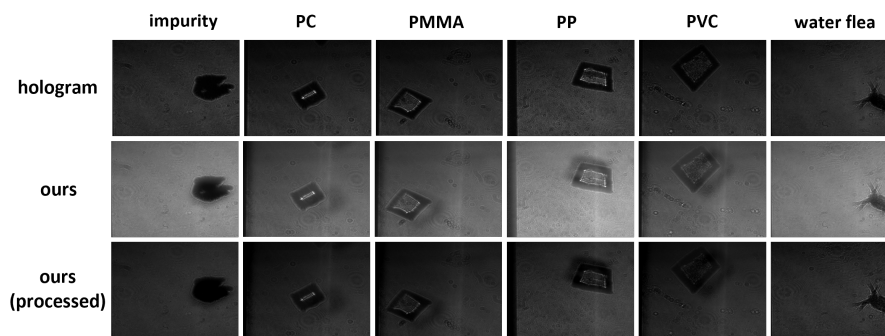


Fig. 2. Examples of holograms, raw images recorded by the system, and pre-processed images for comparison for each particle type.

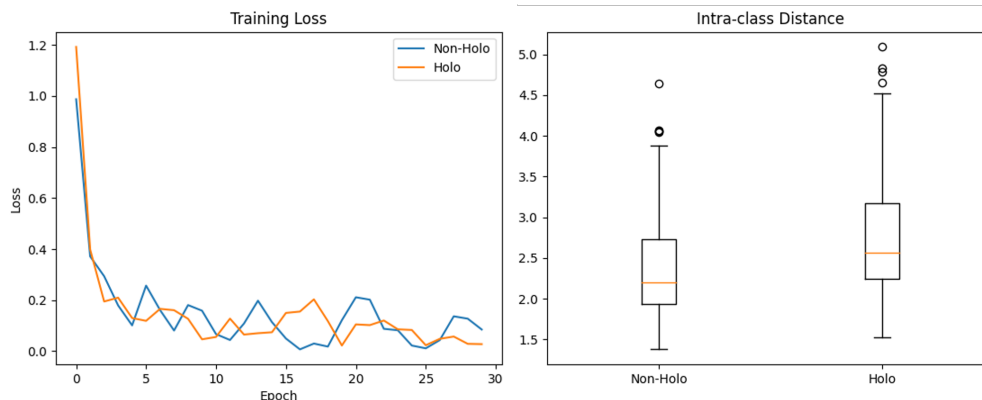


Fig. 3. Results from supervised classifications using AlexNet.

This integrated methodology, spanning optical encoding through computational and learning-based analysis, establishes a complete, high-throughput pipeline for comprehensive 4D particle monitoring and characterization.

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References

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