A field deployable imaging system for detecting microplastics in the aquatic environment

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***Abstract*—Microplastic (MP) pollutants, which are widely distributed and resistant to decomposition, pose serious threats to both ecosystems and human health. Developing efficient, field deployable, and low-cost MP detection systems is of paramount importance for promoting sustainable development. In this work, we design an integrated imaging system for detecting MPs in various aquatic environments. To address the challenge of image degradation caused by scattering effects, a de-scattering algorithm based on synthetic polarization holography is proposed. Calibration results demonstrate a substantial enhancement in image contrast and spatial resolution. Furthermore, our imaging system enables simultaneous capture of amplitude, phase, and polarization information, which is advantageous for the quantification and identification of MPs. Consequently, this field deployable imaging system offers an efficient solution for real-time monitoring of MPs in turbid aquatic environments.**

***Index Terms*—Microplastic detection, imaging system, polarization, holography, scattering media.**

I. Introduction

MP pollution has emerged as a pressing global issue [1], [2], posing significant threats to sustainable development. It has been reported that MPs are found in various aquatic environments, including oceans, rivers, lakes, and polar regions [3]. Due to their small size and resistance to degradation, MPs can propagate along the food chain and eventually accumulate in the human body, causing various health problems [4]. Traditional detection approaches typically involve laborious environmental sampling, sample pre-processing, and laboratory-based analysis [5], [6]. However, such costly and cumbersome methods are inadequate to address the growing problem of MP pollution. To achieve the sustainable development goal of clean water and sanitation, there is an urgent need to develop efficient detection systems for assessing MP contamination in diverse aquatic environments.

From the perspective of sustainable development, the desired MP detection system should primarily focus on three objectives. Firstly, considering the extensive dispersion of MPs in various scenarios, the detection system should be field deployable, allowing for *in situ* characterization of MPs [7]. Secondly, the system's cost should be affordable for widespread adoption, enabling extensive deployment in different regions to facilitate timely monitoring of global MP evolution [8]. Lastly, the system should possess robust detection capabilities [9], including high-throughput analysis, automatic particle quantification, and accurate identification of MPs. By fulfilling these objectives, the detection system can greatly contribute to comprehensive MP assessment, thereby informing the development of effective measures to reduce MP contamination.

Digital holography (DH) holds great potential as a promising tool for *in situ* particle characterization [10]–[12], offering unique advantages such as label-free imaging, non-invasive sample handling, and volumetric reconstructions. Its simple optical configuration and powerful imaging capability have led to the development of portable instruments for underwater monitoring of planktons and microorganisms. Moreover, preliminary attempts have been made in applying DH approaches to MP detection. For example, Bianco et al. [13], [14] and Merola et al. [15] developed an off-axis holographic imaging system for MP classification. They found that the retrieved phase maps [14] and the Jones matrix [16] of MPs are informative features for material differentiation. Zhu et al. [17]–[19] demonstrated the feasibility of deep learning-based approaches in extracting holographic features for MP identification. However, the presence of scattering media poses a significant challenge when implementing underwater holographic imaging. The scattering effects caused by micro/nano-particles in complex media often result in image degradation and reduced accuracy in particle detection. Previous studies have not yet investigated the influence of scattering media on MP detection.

In this work, we propose a field deployable imaging system specifically designed for detecting MP particles in turbid aquatic environments. It is based on the integration of DH and polarization imaging [20], [21], offering two key advantages. Firstly, it allows for the extraction of more distinctive features from the polarization response of MPs [22], [23], enhancing the system's robustness. Secondly, it enables the establishment of an advanced de-scattering algorithm to mitigate the effects of scattering media and improve image quality. The results of calibration and proof-of-principle experiments demonstrate its effectiveness in detecting MPs through scattering media. We believe that this innovative approach will significantly contribute to ongoing efforts to monitor and mitigate MPs in aquatic ecosystems, thereby promoting sustainable development and environmental stewardship.

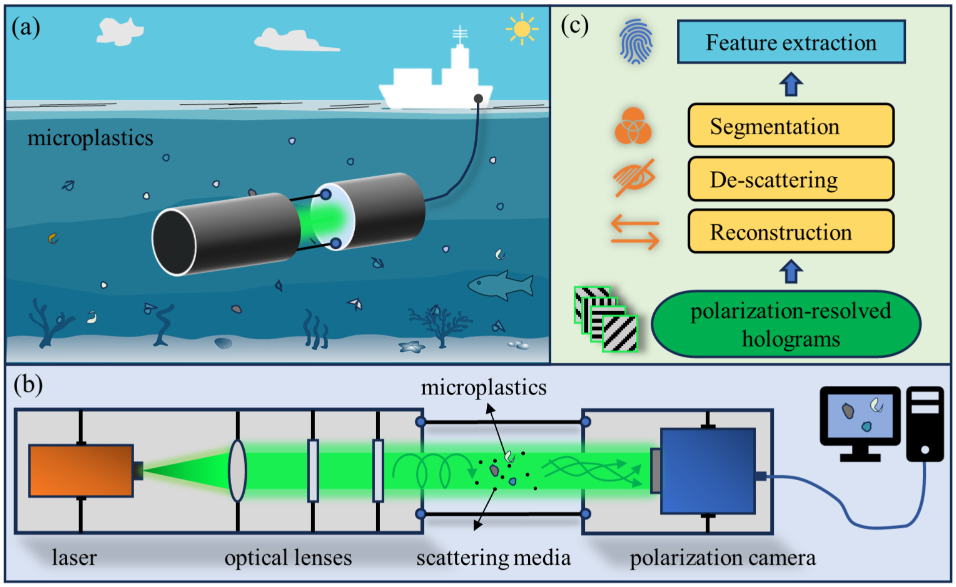

Fig. 1. Schematic diagram of the microplastic detection system. (a) The imaging system is field deployable for various aquatic environments. (b) The optical configuration of polarization-sensitive digital holography. (c) The flow chart of image processing.

II. Imaging System

A. Optical configuration

The schematic diagram of the field deployable imaging system is depicted in Fig. 1. This compact, portable, and cost-effective device empowers rapid detection of MP particles in various aquatic environments. As illustrated in Fig. 1(a), researchers can conveniently perform extensive and high-frequency assessments of MP pollution, circumventing the need for labor-intensive environmental sampling and laboratory-based analysis.

The optical configuration of the system, based on the integration of polarization imaging and digital in-line holography, is depicted in Fig. 1(b). The setup primarily comprises a continuous-wave laser ($\lambda = 532\,\mathrm{nm}$), three optical lenses (i.e., a collimating lens, a polarizer, and a quarter wave plate), and a polarization camera (MC-A500P-163, Crevis Tech, South Korea). For waterproofing purposes, two plastic shells encapsulate all the components and are connected together by two metal bolts. The detection volume ($8.5\,\mathrm{mm}\times 7.1\,\mathrm{mm}\times 50\,\mathrm{mm}$) is located within the gap between the shells. MP particles within the scattering media are illuminated by the circularly polarized coherent light, resulting in the generation of distinct holographic fringes and polarization responses. These informative patterns are subsequently captured by the camera as polarization-resolved holograms. Moreover, the system's power and signal are transmitted through cables, simplifying the structure of the imaging probe.

B. Image processing

The flow chart of image processing is briefly illustrated in Fig. 1(c). In each single shot, four holograms corresponding to specific linear polarization directions ($0°$, $45°$, $90°$, and $135°$) are simultaneously captured. In a conventional manner, the hologram is numerically reconstructed using back-propagation algorithms, such as the angular spectrum function [24]. The mathematical expression is

$$\Gamma = \mathcal{F}^{-1}\left\{\mathcal{F}(h) \times \exp\left(-i\frac{2\pi z}{\lambda}\sqrt{1-\lambda^2 f_x^2 - \lambda^2 f_y^2}\right)\right\}, \tag{1}$$

where $\Gamma(x, y, z)$ denotes the reconstructed complex optical field of the hologram $h(x, y)$ at the depth z, $\mathcal{F}$ represents the Fourier transform, and f_x and f_y are the transverse spatial frequencies. However, due to scattering effects, the holograms captured underwater are considerably degraded by noise, leading to poor visibility and low spatial resolution.

To solve this problem, a de-scattering algorithm is proposed in this work. Firstly, a synthetic hologram h_s is generated by randomly selecting each pixel from the four polarization directions. It can be expressed as

$$h_s(x, y) = \sum_{j=0°,45°,90°,135°} s_j h_j(x, y), \tag{2}$$

where j denotes the four polarization directions, s_j is the weight matrix such that each pixel of h_s is randomly determined only once in the four polarization directions. Secondly, the synthetic hologram is consecutively reconstructed at a series of depths around its in-focus depth z_r. The number of reconstructions is denoted as D, and the depth interval is set as $\Delta z = 10\,\mu\mathrm{m}$. Averaging the D reconstructions of a single synthetic hologram can enhance the image quality, which is mathematically expressed as

$$\mathrm{E}_D(x, y) = \frac{1}{D}\sum_{z=z_r-\frac{D}{2}\Delta z}^{z_r+\frac{D}{2}\Delta z} \Gamma_s(x, y, z). \tag{3}$$

Because the majority of image-bearing photons are ballistic photons that maintain their coherence property and have a larger depth of focus compared to scattered photons. Eventually, with the N randomly synthesized holograms (the index is n), the final image is obtained by averaging the N distinct reconstructed optical fields $E_D(x, y)$, which can be expressed as

$$\mathrm{E}_N(x, y) = \frac{1}{N} \sum_{n=1}^{N} \mathrm{E}_D(x, y). \tag{4}$$

The reason for image enhancement is that, by averaging the reconstructed optical fields of the synthetic holograms, the unwanted scattered photons with arbitrary polarization states can be suppressed, while the ballistic photons can be well-preserved due to their resistant polarization states. Additionally, segmentation of particle projections is performed using the adaptive threshold method. It helps to distinguish and isolate the MP particles within the image.

Multiple features are automatically extracted from the reconstructions to quantify and identify MPs. For example, particle shape, size, and abundance can be determined from the segmentation of the amplitude map. The phase map can reveal variations in the refractive index or thickness of particles, allowing for discrimination between different types of particles. The polarization response, such as the degree of linear polarization (DoLP) and angle of polarization (AoP) [25], can help distinguish MPs from other natural particles based on their unique polarization signatures. The mathematical expressions of DoLP and AoP are

$$\mathrm{DoLP}(x, y) = \frac{\sqrt{Q^2(x, y) + U^2(x, y)}}{I(x, y)}, \tag{5}$$

$$\mathrm{AoP}(x, y) = \frac{1}{2} \tan^{-1} \frac{U(x, y)}{Q(x, y)}, \tag{6}$$

where I, Q, U are the linear Stokes parameters calculated from the four polarization-resolved holographic reconstructions.

III. Results and Discussion

A. Calibration

In the evaluation of the de-scattering algorithm, a calibration is conducted by imaging a USAF-1951 target through pure water and a milk solution respectively. The hologram obtained in water serves as the ground truth since very few scattering particles are present. The volume concentration of the milk solution is 0.4%, resulting in considerable scattering effects along the light path. The distance between the target and the image sensor is approximately $30\,\mathrm{mm}$. As shown in Fig. 2(e), the reconstruction of the hologram captured through the milk solution shows image degradation, characterized by low contrast and spatial resolution. However, by averaging 60 reconstructions of 40 synthetic holograms, the reconstructed image, as shown in Fig. 2(f), exhibits a significant enhancement in image quality. Quantitatively, the correlation coefficient (cc) between the reconstructions of the milk hologram and the ground truth improves from 0.787 to 0.916. In addition, the

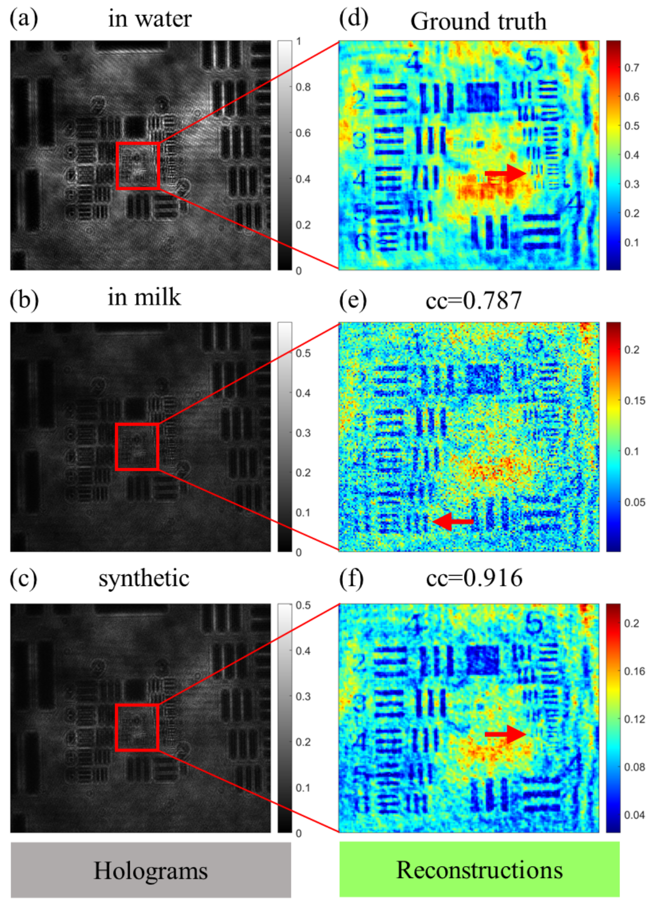

Fig. 2. Visualization of (a) the hologram in pure water, (b) the degraded hologram in milk solution, and (c) the synthetic hologram. (d-f) The corresponding holographic reconstructions. The red arrow indicates the smallest countable group of bars in the USAF-1951 target. cc: correlation coefficient.

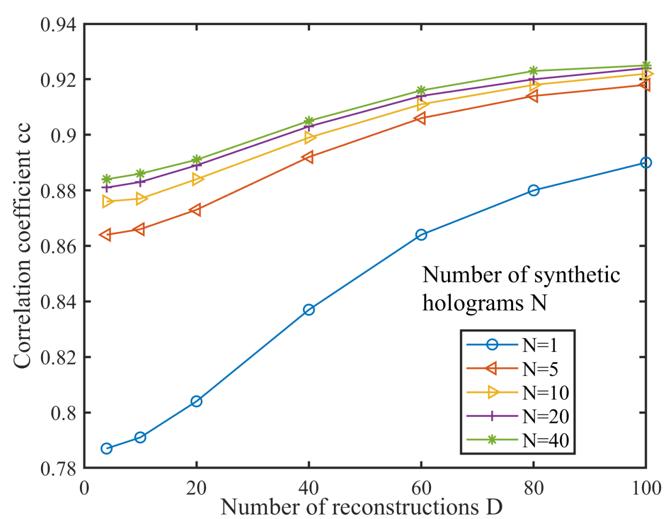

Fig. 3. Evolution of reconstruction performance (the correlation coefficient cc), as a function of the number of reconstructions D and the number of synthetic holograms N.

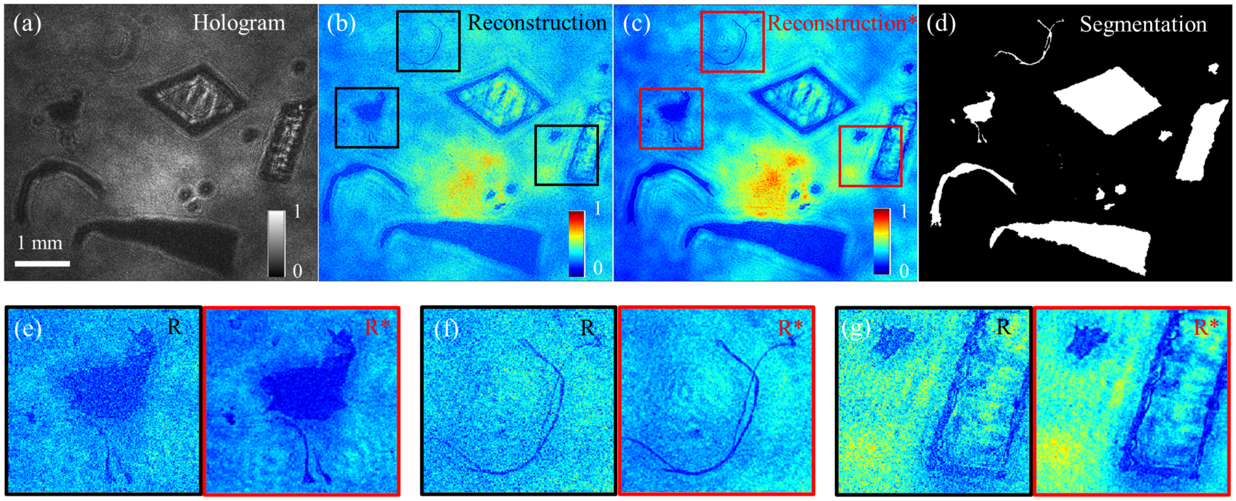

Fig. 4. Visualization of particle detection in the milk solution. (a) The degraded hologram due to scattering effects. (b-c) The reconstructions without and with de-scattering, respectively. (d) The segmentation of particle projections. (e-g) The comparison between (b) and (c) with magnified images.

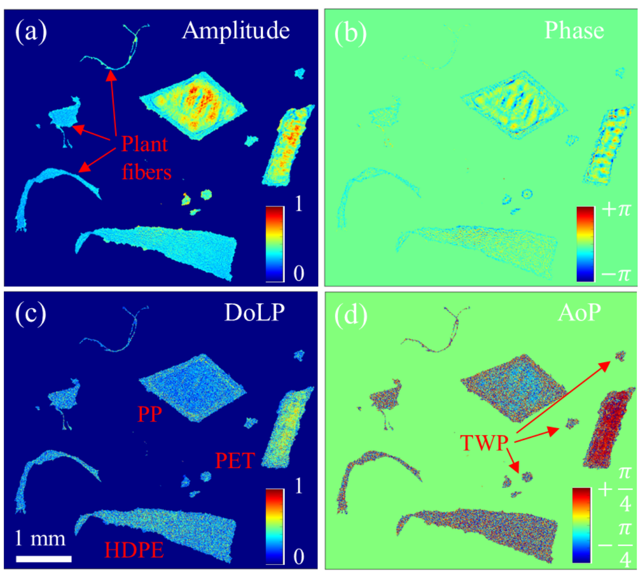

Fig. 5. The extracted features of (a) amplitude, (b) phase, (c) DoLP, and (d) AoP, of the particles.

spatial resolution, indicated by the red arrows in Fig. 2(d-f), improves from $28.51\,\mathrm{lp/mm}$ to $50.8\,\mathrm{lp/mm}$.

Furthermore, the influence of key parameters (D and N) on the enhancement is quantitatively investigated. As shown in Fig. 3, when considering a single synthetic hologram ($N = 1$), averaging D reconstructions yields a significant improvement in image quality as D is increased from 4 to 100. It demonstrates that the scattered photons can be suppressed to a certain extent, as indicated by $cc = 0.886$. To further enhance image quality, increasing the number of synthetic holograms N is also an effective strategy. This is because the scattered photons with arbitrary polarization states can be suppressed during the averaging process. Nevertheless, a saturation state ($cc = 0.924$) occurs in the conditions of $D \geq 80$ and $N \geq 40$. Consequently, to optimize the computational costs while still achieving significant enhancement, it is recommended to set D and N below these saturation thresholds.

B. Particle detection

Proof-of-principle experiments are conducted to detect MP particles, plant fibers, and tire wear particles (TWP) through the milk solution. The MP particles are generated from disposable plastic cups, gloves, and bags, with materials including polyethylene terephthalate (PET), polypropylene (PP), and high-density polyethylene (HDPE). As a result, the degraded hologram and the corresponding reconstruction and segmentation are illustrated in Fig. 4. Leveraging the advantage of flexible refocusing, our imaging system is capable of reconstructing sharp images of these fine particles without mechanical focus scanning. Moreover, a comparison between the reconstructions without and with the proposed de-scattering algorithm is displayed in Fig. 4(e-g). An improved image quality with sharper particle edges and stronger image contrast is achieved. It is of great importance for the imaging system's ability to detect smaller particles and extract more detailed particle features. Consequently, the segmentation of particle projections enables the quantification of particle size, shape, and abundance.

Based on the segmentation, the distributions of amplitude, phase, DoLP, and AoP of these particles are extracted. As shown in Fig. 5, MP particles exhibit distinguishable features compared to plant fibers and TWP. For instance, the PP and PET particles are sensitive to the circularly polarized light, showing unique responses in DoLP and AoP. This arises from the differences in their optical properties, such as refractive index, transmittance, and birefringence. Compared to traditional chemical analysis methods, the integrated imaging system facilitates rapid and timely identification of MP particles in a more practical manner.

IV. Conclusion

In summary, we develop a field deployable imaging system that integrates polarization imaging and digital holography. To tackle the critical issue of image degradation owing to scattering media, a de-scattering algorithm is proposed to suppress the scattered photons by utilizing polarization and coherence properties. Both calibration and experiments demonstrate a substantial improvement in image quality. Consequently, this compact imaging system enables efficient feature extraction for quantifying and identifying MP particles in the aquatic environment. The simplicity and accessibility of our system make it a promising solution for water monitoring and sustainable development.

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