Snapshot polarization-sensitive holography for detecting microplastics in turbid water

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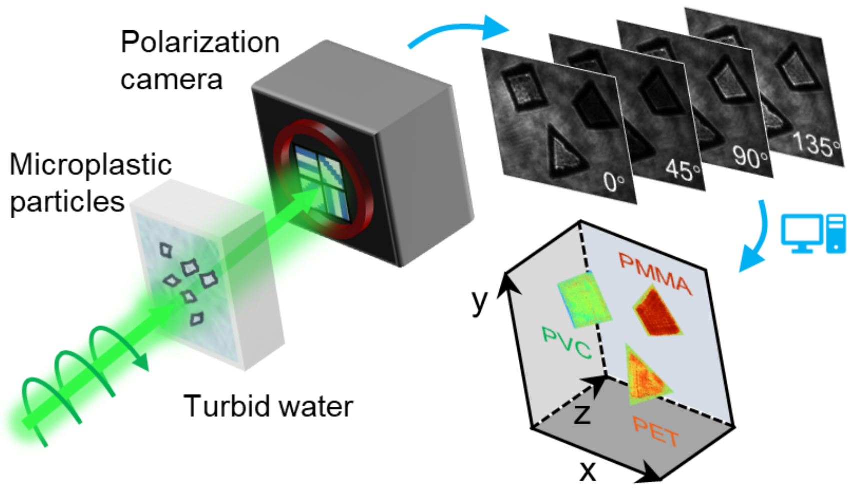
Abstract

Microplastic (MP) pollution is a serious environmental problem, which can severely harm the earth's ecosystems and human health. However, *in situ* characterization of MP particles remains challenging due to the complex natural environments, such as turbid water. In this work, a hybrid computational imaging approach based on holography and polarimetry is developed for rapid and accurate assessment of MP pollution in turbid water. In particular, the influence of scattering media on MP detection is experimentally studied. With a compact optical configuration and an efficient computational method, this imaging system is capable of seeing through scattering media and obtaining multimodal information about the object in a snapshot. The results suggest that polarization features can substantially improve image contrast even in highly turbid water. In addition, it is demonstrated that the polarization properties of objects are new discriminative features for identifying MP materials. Therefore, such a portable system is extremely useful for further development of MP monitoring in natural environments.

Keywords: Microplastic, polarization imaging, digital holography, scattering media

TOC Graphic



Introduction

Microplastic is one of the most harmful pollutants,[1,2] which has been extensively dispersed in air, soil, and water.[3] Most MPs decompose extremely slowly in the natural environment and the number of MPs has been growing rapidly.[4] MPs enter into various wildlife along the food chain and eventually accumulate in the human body, causing long-term adverse impacts on the ecological environment and human health.[5,6] However, the ability to study and control MP pollution is hindered by the lack of technologies for the rapid and *in situ* characterization of environmental samples. Traditional methods employed in laboratories for MP detection,[7] such as Raman spectroscopy and Fourier transform infrared spectroscopy, are inherently incapable of addressing this issue. One reason is that, the sample pre-processing procedures required in these methods are rigorous, laborious, and time-consuming, resulting in low-throughput analysis and screening.[8] Another is that, the specialized equipment for spectroscopic analysis is usually expensive and sensitive to operation conditions.[9] Thus, to realize fast and accurate monitoring of global MP pollution, new detection approaches with simplified procedures, low cost, and portable devices are strongly needed.[10]

In particular, MPs are usually found in turbid aquatic environments where the complex media inevitably leads to the degradation of detection accuracy and robustness. For instance, when performing underwater imaging of MPs, poor image quality due to absorption and scattering effects makes it challenging to characterize the targets. Therefore, it should be of great significance to evaluate and understand such degradation phenomenon when detecting MP particles through various scattering media. Unfortunately, most previous studies attempting to detect MPs in the aqueous phase[11–14] have ignored this critical issue. They either placed the pre-treated MP samples in clean media for observation, or paid less attention to the variation of the employed water media. The evaluation of their classification criteria in turbid water is missing. In the present work, we address this knowledge gap by developing an *in situ* characterization method to overcome the influence of turbid water on MP detection.

Researchers around the world have devoted substantial efforts to the development of portable MP detection tools.[10,15,16] Specifically, optical imaging techniques are the most promising candidates due to their distinctive advantages of simple optical setup, fast response, non-contact and non-destructive sensing. When plastics interact with incident light waves, certain optical phenomena (e.g., absorption, scattering, polarization, diffraction, reflection, etc.) can occur and show specific optical response which is associated with material properties.[10,17] For instance, Philips et al.[18] demonstrated holographic differentiation of plastic-like particles in water, based on the capability of digital holography to measure the particle's refractive index. Specifically, Merola et al.[12] proposed digital holography as a non-invasive technique for identifying MP particles from diatoms. Bianco et al.[13,19,20] further developed their off-axis holographic imaging system for MP classification by introducing fractal parameters and the Jones matrix. They showed that the holographic fingerprint is informative and can offer new possibilities for environment monitoring. Meanwhile, Zhu et al.[11,21,22] explored the feasibility of deep learning-based holographic methods for identifying different types of MPs. They demonstrated that the discriminative information about the MP samples encoded in the holograms can be extracted using deep learning approaches.

Besides, polarimetry, which is the measurement and interpretation of the polarization of transverse waves, also has great potential for MP detection. For example, Sierra et al.[14] attempted to use polarized light optical microscopy to identify MPs in wastewater samples, of which the feasibility was supported by confocal Raman microscopy and near-infrared spectroscopy. Labbe et al.[23] reported that polarization imaging combined with Nile Red fluorescence microscopy is a useful tool for MP identification. Li et al.[24] recently developed a Mueller matrix polarimetry setup for the recognition of MP particles suspended in seawater. Overall, in most of the reported works, holography and polarimetry were employed separately for MP analysis and characterization. And the tested MP samples are often transparent or semi-transparent so that the transmitted light can serve as an information carrier of MP's intrinsic structure and material. These two optical techniques share the unique advantage of simple and low-cost devices, opening up new opportunities for the development of portable MP detection systems.

However, MPs in natural environments are often complex with large heterogeneity,[25] which affects the robustness and efficiency of existing identification methods in various application scenarios. One of the main reasons is that the features employed for MP classification are relatively limited. To obtain more meaningful information and extract more distinguishable features about environmental samples, a promising approach is the integration of holographic imaging and polarization imaging.[26–28] Consequently, the specificity of the detection system can be considerably enhanced. There are notable examples that have explored the implementation of polarization imaging through holographic approaches,[29–31] highlighting the potential for combining these two imaging modalities. In particular, Tahara et al.[32–34] developed a hybrid system coupling incoherent digital holography with polarization imaging, showcasing promising results on polarization-sensitive 3D imaging. Nevertheless, there are very few works on the integration of holography and polarimetry for the detection of MPs.[27,28] Běhal et al. and Valentino et al. have contributed the preliminary attempt at such a strategy.[13,27] They built a hybrid system based on off-axis holographic imaging and two-step Jones matrix polarimetry, demonstrating promising results on the identification of MP fibers. Meanwhile, Zhu et al. and Li et al. are also developing different integrated imaging systems with more compact and automatic configurations.[28,35–37] In their works, a customized fluidic channel and deep learning-based classifiers are adopted to realize high-throughput and dynamic assessment of MPs. Again, the impact of turbid water on these reported methods has not yet been evaluated.

The motivation for the present work is to solve the problem of detecting MPs in turbid aquatic environments by developing a hybrid computational imaging system. Snapshot polarization imaging is embedded into digital in-line holography for simultaneously obtaining both polarimetric and holographic information of MP particles. The integration of two powerful computational imaging techniques enables fast and accurate characterization and identification of MPs while maintaining a simple optical configuration. An efficient computational method based on polarization parameters i.e., degree of linear polarization (DoLP) and angle of polarization (AoP)[38] is proposed to recognize MP particles through scattering media and quantify the optical anisotropy of MP materials. The results demonstrate that AoP can effectively improve image contrast for accurate particle segmentation even in highly turbid water. In particular, it is found that DoLP is an angle-independent feature for distinguishing randomly dispersed MPs with different materials. Finally, the integrated imaging system can substantially promote the development of compact and field-portable devices for automatic MP monitoring in turbid aquatic environments.

Methodology

Experimental setup

The experimental setup to capture holograms of MP particles with polarization analysis is illustrated in Fig. 1. The illumination light is a continuous-wave laser beam at 532 nm wavelength. It is collimated by a convex lens and circularly polarized by a linear polarizer and a quarter wave plate. The fast axis of the quarter wave plate is oriented at 45° with respect to that of the polarizer. There are two major reasons for using circular polarization (CP) rather than linear polarization (LP). One

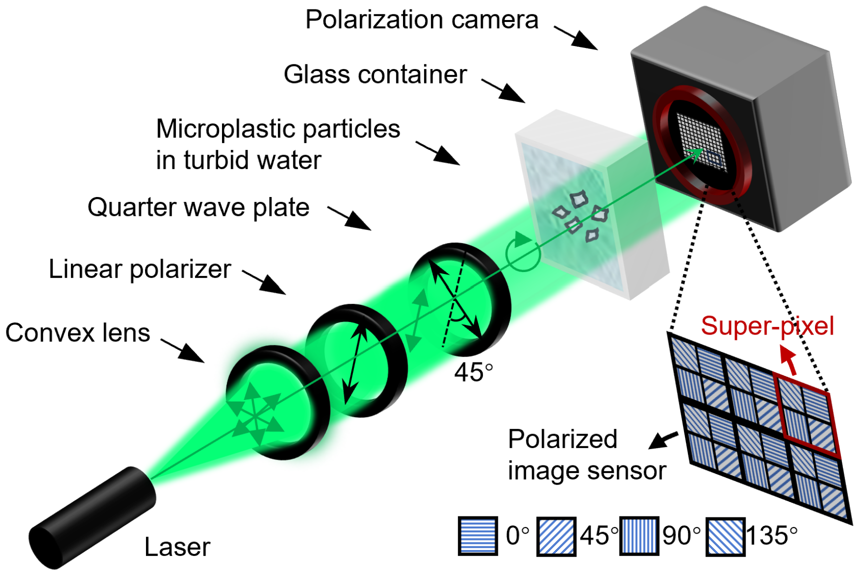


Figure 1: Polarization-sensitive holographic imaging system. Illuminated by a circularly polarized laser beam, the interference pattern of microplastic particles in turbid water is recorded by a polarization camera. A localized region in the polarized image sensor is zoomed in to reveal the arrangement of the pixelated micro-polarizer array. Four adjacent pixels with different polarization orientations constitute a super-pixel.

is that CP light maintains better polarization characteristics than LP when imaging through scattering media.[39] The other is that, CP light is point-symmetric and does not depend on the optical axis orientation of the samples, while variable optical axis angle between the LP light and the samples may introduce additional disturbances to measurement results.

The holographic fringes of MPs are generated due to coherent interference between object light and reference light. In addition, the transmitted light also encodes the polarization response of MPs, which can indicate intrinsic optical anisotropy. Finally, the pattern is recorded by a polarized image sensor (MC-A500P-163, Cameralink, Crevis Tech. South Korea) that is capable of simultaneously measuring the intensity of linear polarization in four orientations (i.e., 0°, 45°, 90°, and 135°). The spatial resolution of the sensor is 2464×2056 with a square pixel size of 3.45 µm. Four adjacent pixels with different polarization orientations constitute a super-pixel. Thus, the spatial resolution of the recorded hologram is reduced by a factor of two both in horizontal and vertical pixel coordinates (i.e., 1232×1028).

Figure 2 shows representative holograms of MP particles in four polarization directions. Not

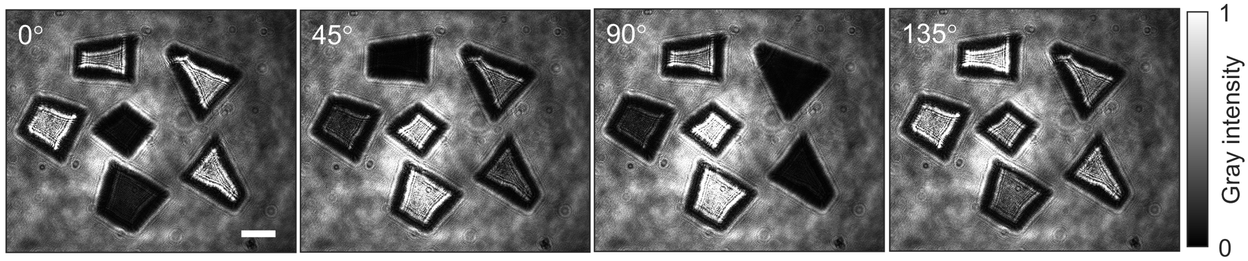


Figure 2: Representative holograms of MP particles in four polarization directions, which are captured in a single shot. Scale bar: 1 mm.

only holographic fringes but also polarization responses are visible. The considerable differences between holograms in different directions indicate that the MP particles are sensitive to polarized light. The four holograms captured in a single shot could carry abundant information for particle characterization and material identification. It should be emphasized that this imaging system does not increase the complexity of traditional in-line holography configuration while enhancing the capability of MP material discrimination. With this simple and compact optical configuration, each particle in the field of view can be detected and 3D-tracked without any mechanical focus scanning. Moreover, no manual adjustment of the polarization generator or analyzer is required. Compared with the previous MP detection system, which combined off-axis holographic imaging and two-step polarization imaging,[13] our system is significantly more compact and suitable as a portable device.

MP samples as well as other natural particles are suspended in pure water or milk solutions to simulate turbid aquatic environments. It is a common strategy to adjust the scattering effect by controlling the concentration of milk solutions.[40,41] A series of milk solutions with gradually increased concentrations are employed in this work. The scattering effect of the media is quantified using the concept of optical depth.[42] The size of the transparent glass container is $20\,\text{mm} \times 20\,\text{mm} \times 12\,\text{mm}$. The distance between the image sensor and the glass container is around 20 mm. Five types of commonly used plastic sheets are purchased (Xinsheng Plastic Material Company, China), namely, polymethyl methacrylate (PMMA), polyethylene terephthalate (PET), polycarbonate (PC), polypropylene (PP), and polyvinyl chloride (PVC). They are manually cut to be small irregular fragments with a size of around 1 mm. Note that all MP particles tested in this work are transparent and colorless, so it is difficult to distinguish them with the naked eyes. These controlled samples enable us to eliminate the interference of non-material factors such as color, shape, and surface characteristics. They serve as a benchmark for validating the effectiveness of our imaging system and laying the foundation for further research.

Computational method

The computational method employed in our hybrid imaging system mainly includes numerical reconstruction of holograms and polarization features extraction. Digital holography is a versatile imaging technique for label-free, non-destructive, non-invasive measurement of soft matters in various application scenarios.[43,44] As the complex wavefront is encoded in the captured holograms, numerical reconstruction can be performed to reveal the distributions of amplitude and phase at any flexible depth. As an extensively adopted method, the angular spectrum function[45] is used to calculate the light forward or backward propagation, which is mathematically expressed as

$$\Gamma(x,y,z) = \mathscr{F}^{-1}\left\{\mathscr{F}\left[E_R^*(x,y)h(x,y)\right] \times \exp\left(-i\frac{2\pi z}{\lambda}\sqrt{1-\lambda^2 f_x^2 - \lambda^2 f_y^2}\right)\right\}, \tag{1}$$

where $\Gamma(x,y,z)$ represents the reconstructed complex wavefront with coordinates (x,y,z), $\mathscr{F}$ denotes the Fourier transform, E_R^* is the complex conjugate of the reference wave, h is the captured hologram, λ is the wavelength of illumination light, and f_x and f_y are the transverse spatial frequencies.

After a series of reconstructed images at different depths are obtained, autofocusing algorithms[46–48] are employed to determine the in-focus depth for each particle in the field of view. With the advantage of flexible refocusing, the out-of-focus problem in traditional microscopy is well addressed. Therefore, useful information about the target, such as the shape, size, amount, and 3D location, can be quantitatively analyzed. Featuring automatic recognition and segmentation of particle edges, the clustering-based particle detection (CBPD) method is adopted in this work. Multiple autofocusing criteria are utilized in this method, which can offer more robustness by reducing the detrimental effects of various experimental factors. More details about the CBPD method can be found in.[49,50]

With the reconstructed in-focus images in different polarization directions, extraction of polarization features is implemented. Polarization is an important descriptor of electromagnetic wave and contains intrinsic information about the tested objects that traditional intensity-based sensors ignore.[51] Polarization imaging is an emerging and advanced technique for the investigation of materials with optical anisotropy. Due to the specifically ordered arrangement of molecules and small structures, the polarization response of different materials often shows different features, which makes it possible to identify MP particles with birefringence. Thus, significant efforts have been devoted to the development of polarization-sensitive imaging system[52–54] and the extraction of polarization features, such as Jones matrix, Stokes parameters, and Mueller matrix.[13,55,56] In this work, linear Stokes parameters are adopted to describe the polarization of the light:

$$I(x,y) = I^{0}(x,y) + I^{90}(x,y), \tag{2}$$

$$Q(x,y) = I^{0}(x,y) - I^{90}(x,y), \tag{3}$$

$$U(x,y) = I^{45}(x,y) - I^{135}(x,y), \tag{4}$$

where I represents the grayscale intensity of a reconstructed image at a certain polarization direction (indicated by the superscript). Furthermore, to characterize the polarization response of MPs, specific polarization parameters can be deduced from Stokes parameters, such as the degree of linear polarization[38] (DoLP $\in [0,1]$)

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

and the angle of polarization[38] (AoP $\in [-\frac{\pi}{4}, +\frac{\pi}{4}]$)

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

Both AoP and DoLP of the light transmitted through the MP samples contain meaningful information on the molecular orientation distribution and the anisotropy of molecular optical properties. To the best of our knowledge, the potential of identifying MP particles using DoLP and AoP has not yet been evaluated. In addition, these two polarization parameters have superior resistance to media's scattering effect than traditional intensity-based images. Thus, an enhanced image quality can be obtained with the extracted polarization features.

Results and discussion

In order to achieve *in situ* characterization and identification of MP pollutants, it is necessary to investigate the effect of turbid water on the performance of our designed imaging system. Firstly, the extraction of polarization features from the polarization-resolved holographic images is implemented. Then, the influence of scattering media (e.g., micro/nano-particles, which may cause image degradation due to scattering and absorption effects) and natural particles (e.g., microorganisms, which may lead to wrong identification of MPs) is considered in this work. Finally, the capabilities of 3D imaging and classifying different MP materials are evaluated. The results of these critical issues are presented in this section.

Extraction of polarization features

When performing numerical reconstruction of the polarization-resolved holograms, we firstly investigated the relationship between the reconstruction distance and the birefringence properties of MP samples. Figure 3 illustrates the extracted DoLP and AoP of a PMMA particle as a function of reconstruction distance. It is suggested that the mean value of the measured birefringence properties keeps consistent for a wide range of reconstruction distances. Although twin-image exists because of the in-line holographic configuration, at the particle size scale around 1 mm, the twin-image problem is relatively insensitive to polarization direction. In other words, twin-image shows the same holographic pattern in different polarization directions. Therefore, the extraction

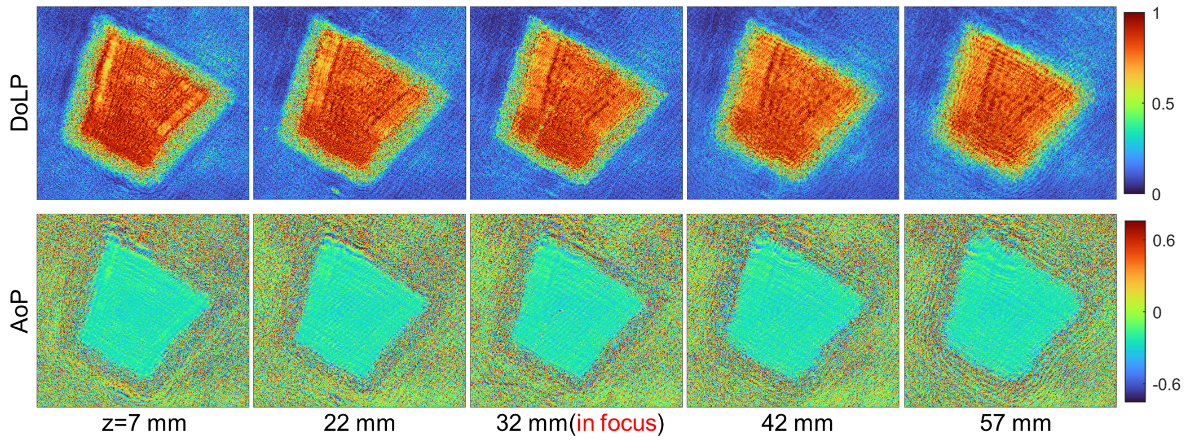


Figure 3: Evolution of DoLP and AoP of a PMMA particle as a function of reconstruction distance. The images are reconstructed at one in-focus depth and four out-of-focus depths, respectively.

of polarization features should not be significantly influenced by the numerical reconstruction of the holograms.

Specifically, the particle image is in focus at the reconstruction distance of 32 mm, while it is out of focus at the other distances, of which five representative reconstructed images are demonstrated in Fig. 3. Although they show consistent mean values at in-focus depth or out-of-focus depth, the in-focus image has a sharper particle edge and uniform distribution. Slight perturbations in the distributions of DoLP and AoP might result from the discrete forms of image recording and reconstruction. Consequently, we segment particle projections and extract DoLP and AoP features from the in-focus reconstructed images in this work. In addition, it should be noted that MP's birefrigence properties are independent of particle geometrical parameters (e.g., shape, area, size, perimeter, etc.). Nevertheless, the measurement of DoLP and AoP could be disrupted by artifacts originating from the twin-image, as the particle size becomes extremely small. Due to the limited spatial resolution of the current imaging system, it is recommended to extract reliable polarization features for particles that have a size lager than 100 µm. In the following proof-of-principle experiments, we primarily focused on MP particles with a size of around 1 mm, which enables to circumvent the interference caused by the twin-image and obtain meaningful polarization information.

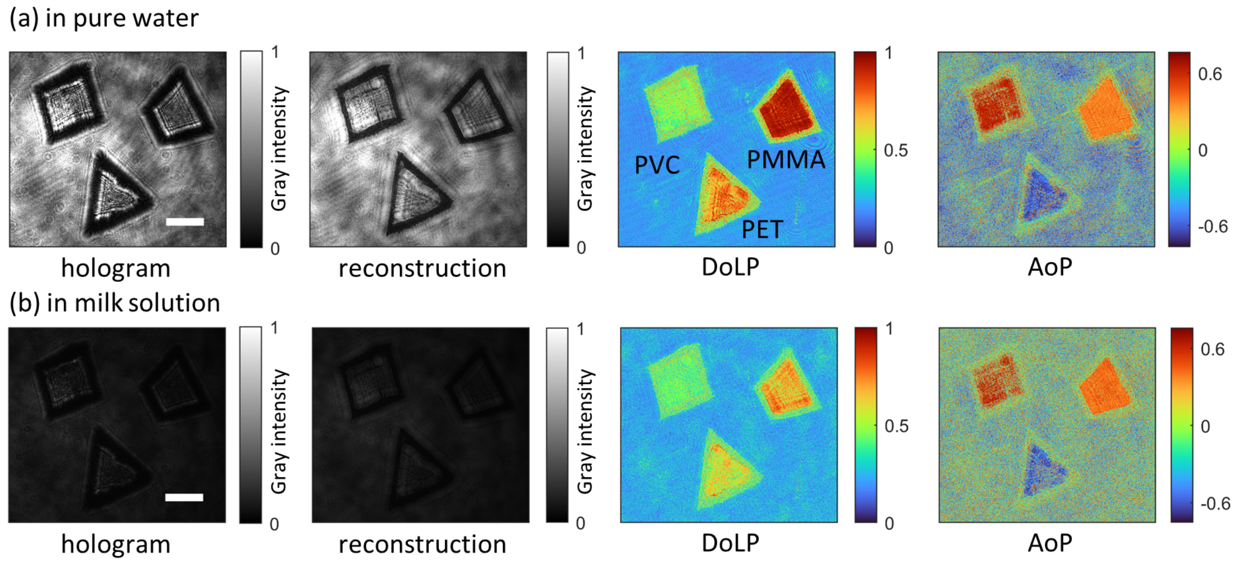


Figure 4: Image degradation due to scattering and absorption effects in the aqueous phase. The holographic and polarimetric images of MP particles in (a) pure water and (b) milk solution, respectively. Scale bar: 1 mm.

Influence of scattering media

Figure 4 shows the comparison of holographic and polarimetric images in the media of pure water and milk solution. Intuitively, image degradation due to scattering and absorption effects in the milk solution is observed. The interference fringes and particle edges are difficult to distinguish from the degraded hologram and the corresponding reconstructed image (i.e., the amplitude map). Hence, only a few useful characteristics of the MP particles could be estimated, which is also a drawback of traditional intensity-based imaging devices working underwater. For instance, it is challenging to extract the fractal parameters[20] or visual features[22] if only the degraded intensity maps are available. However, due to the capability of resolving polarization responses, additional DoLP and AoP features can be obtained using the proposed computational method. Based on these features, image degradation is significantly eliminated and image contrast is dramatically improved. It enables us to see through scattering media and detect MP particles in turbid water. Furthermore, the polarization features are of great potential for classifying different MP materials, which will be discussed in detail in the following subsection.

Taking typical PMMA material as an example, the quantification of degradation ratio and image

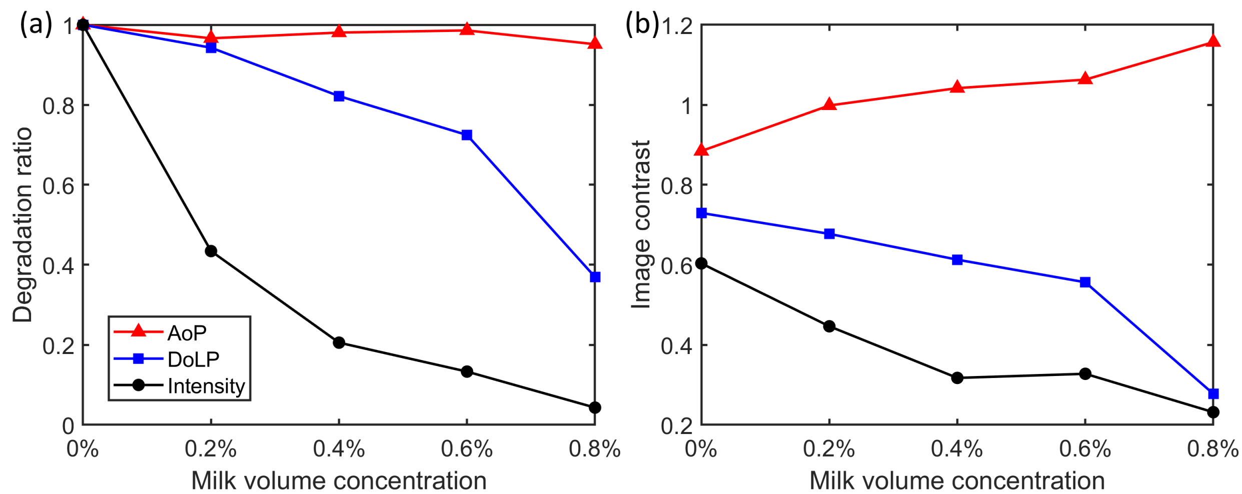


Figure 5: (a) Degradation ratio and (b) image contrast calculated based on the intensity, DoLP, or AoP, as a function of the volume concentration of milk solutions.

contrast under different scattering media is illustrated in Fig. 5. The degradation ratio D is defined as the mean value of the projected region of particles between milk solution $P_m(x,y)$ and pure water $P_w(x,y)$:

$$D = mean[\frac{P_m(x,y)}{P_w(x,y)}]. \tag{7}$$

Image contrast K is used to evaluate the image quality after degradation, which is expressed as

$$K = \left|\frac{I_{obj}-I_{bkg}}{I_{obj}+I_{bkg}}\right|, \tag{8}$$

where I_{obj} and I_{bkg} represent the mean value of intensity (or DoLP, AoP) in the regions of object and background, respectively. To simulate a series of turbidity, five milk and water mixing proportions are used, i.e., the volume concentration of milk solution is set from 0 % to 0.8 %. The other experimental settings, such as exposure time and particle position, are consistent in the experiments. As shown in Fig. 5(a), the intensity decreases rapidly with the increasing milk concentration, resulting in low image contrast and poor visibility. It indicates that the intensity-based features employed in previous works[19,20,22] may lose effectiveness for MP detection. While, DoLP decreases relatively slower so that more information encoded by polarization can be preserved. Moreover, the degradation of AoP is considerably negligible, suggesting that AoP has a strong resistance to scattering media. In addition, as illustrated in Fig. 5(b), the image contrast based on AoP is significantly superior to the others under all testing conditions. The results demonstrate that the AoP map is a robust feature that enables us to recognize MP particles even in highly turbid water.

Influence of microorganisms

In situ detection of MP particles in the aqueous phase will be inevitably affected by natural particles, especially by a variety of microorganisms. To verify the feasibility of distinguishing MP particles from microorganisms in turbid water, a comparative experiment is conducted using both microorganism samples (i.e., *Daphnia magna* and *Paramecium*) and PVC particles. Three kinds of samples are separately suspended in the turbid water that is sampled from a pond at the University of Hong Kong. As illustrated in Fig. 6(a), all particles are visible in the captured holograms. The exclusive reliance on gray intensity information can lead to inaccurate identification of MP particles. However, as demonstrated in Fig. 6(b) and (c), the polarization features (e.g., the AoP and DoLP maps) of PVC particles and microorganisms is remarkably distinguishable. The tested microorganisms have much weaker birefringence properties so their AoP and DoLP maps are consistent with the background. Moreover, PVC particles exhibit substantially discriminate polarization signatures, indicating that this material is sensitive to polarized light. Based on the birefringence-dependent polarization features, it is possible to screen MP particles from microorganisms in a simple and automatic manner. In real-world scenarios, MP particles may be covered by bacteria biofilms or microalgae. By simultaneously extracting polarization features and obtaining refocused sharp images, our imaging system has the potential to mitigate the interference caused by these bio-materials and enhance the accuracy of MP identification.

3D imaging of MPs

As the complex light field is encoded in the holograms, our imaging system is capable of numerically reconstructing the 3D particle field. The determination of the particles' morphological

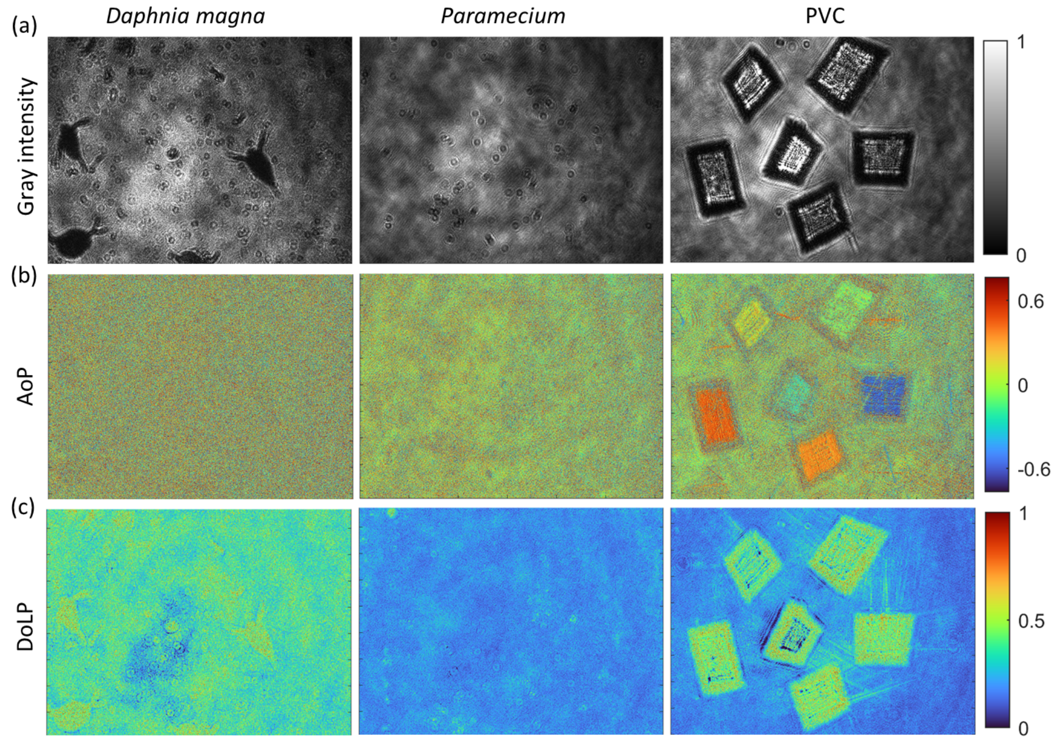


Figure 6: (a) Holograms, (b) AoP maps, and (c) DoLP maps of microorganisms (i.e., *Daphnia magna* and *Paramecium*) and PVC particles.

features is demonstrated here. Figure 7 shows a hologram of various samples including a MP particle, sand, plant fiber and fragments, and dust, which are commonly observed in natural environments. The corresponding refocused images of these particles are marked with blue borders and shown in Fig. 7 as well. Each particle has been successfully reconstructed with a sharp edge and characteristic shape, which contributes to the quantification of particle size and 3D location of the centroid. Thus, the spatial distribution and abundance of particles in the volume of interest can be obtained. The information about particles' shape, size, location, and abundance is of great value for designing specific particle sieving and filtration systems. Compared with traditional direct imaging modalities[14,57] that often suffer from the out-of-focus problem, our holographic imaging system circumvents the requirement of cumbersome mechanical focus scanning. Only a snapshot hologram is needed to restore the 3D scene, with the depth of field extending to tens of centimeters. Therefore, in practical applications, high-frequent and timely characterization of MP pollution could be performed in various monitoring sites.

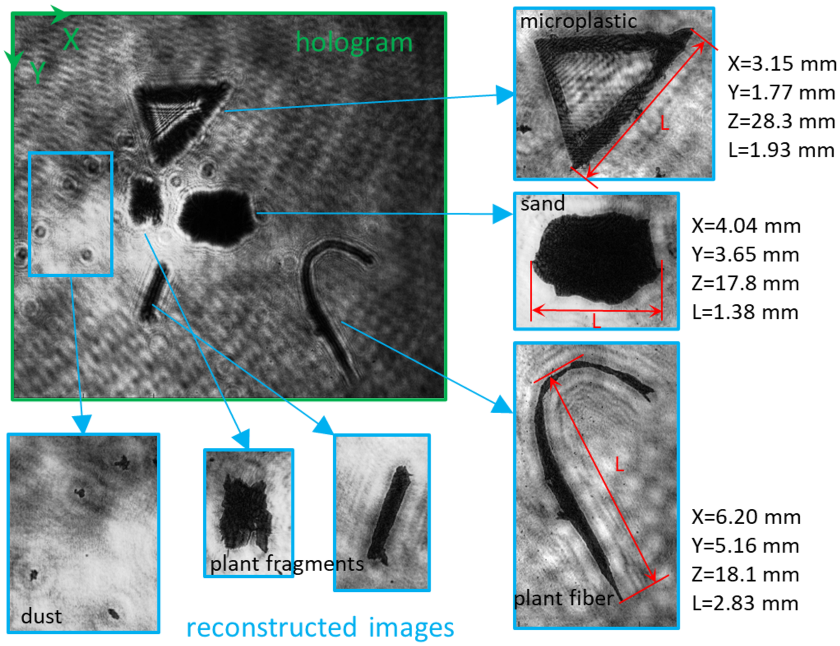


Figure 7: Numerical reconstruction of holograms for revealing particles' morphological features. The samples include a MP particle, sand, plant fiber and fragments, and dust, showing characteristic shapes, sizes, and 3D locations.

In particular, the lateral spatial resolution of our imaging system plays a key role in the measurement of particle size. The influence of scattering media on this issue is quantitatively studied. A USAF-1951 target (Edmund Optics) is used for resolution characterization with the recording distance of 30 mm. With numerical reconstruction using the angular spectrum algorithm, the resolution limit is determined by identifying the last group of bars that can be correctly counted in the reconstructed image. As shown in Fig. 8, the spatial resolution gradually degrades from 20 µm to 62 µm as the milk concentration increases from 0 % to 0.8 %. Therefore, the size of the smallest detectable particle should be larger than this threshold. In addition, two reconstructed images of the target in the case of pure water and the case of milk solution with 0.8 % concentration are illustrated in Fig. 8. Degraded spatial resolution and lower image contrast caused by scattering media can be observed. The results demonstrate that scattering media is a major factor limiting the performance of imaging systems on determining particle size. It also indicates the importance of evaluating MP detection methods in turbid water environments.

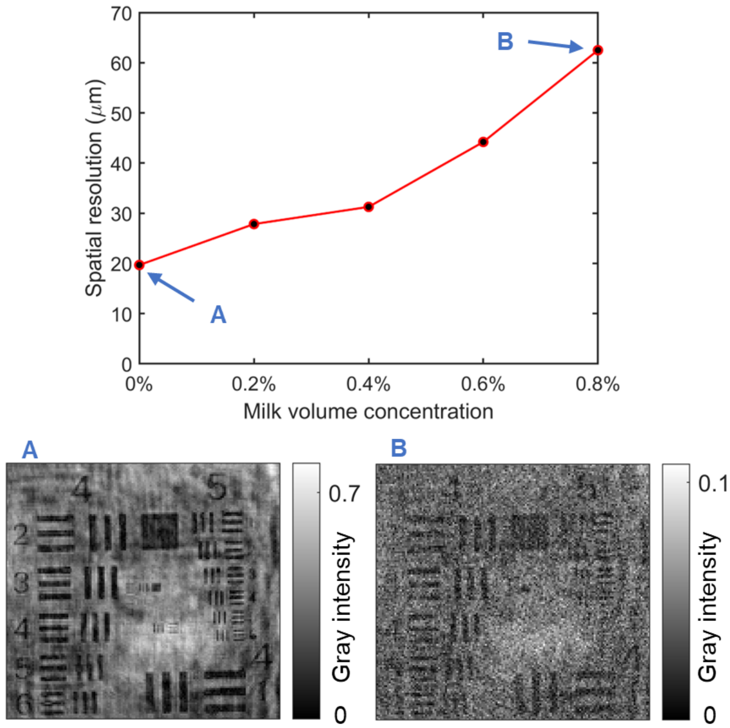


Figure 8: Spatial resolution of the imaging system as a function of the volume concentration of milk solutions. Two reconstructed images of the USAF target are illustrated as well.

Classification of MPs

It is of equal importance to classify different types of MP particles for environmental monitoring. According to the specific birefringence property of different MP materials, their polarization responses are good candidates for classification. Figure 9 shows the color maps of DoLP and AoP of five types of MP particles. In each panel, the particles that have comparable morphologies and sizes are randomly dispersed in the field of view. As expected, these particles are distinguishable by using their DoLP features. For example, PMMA particles have the largest DoLP with a mean value close to unity, while PVC particles have the smallest value in DoLP maps. Furthermore, the distributions of DoLP in the same type of MP particles with different optical axis angles are almost consistent, suggesting that DoLP is an angle-independent feature. Hence, it should be reliable to classify randomly dispersed MP particles by using their DoLP maps. As shown in Fig. 9(b), although AoP is dependent not only on the materials but also on the angle, it is still a useful feature to isolate MP particles with respect to the background. Besides, to evaluate the impact of particle

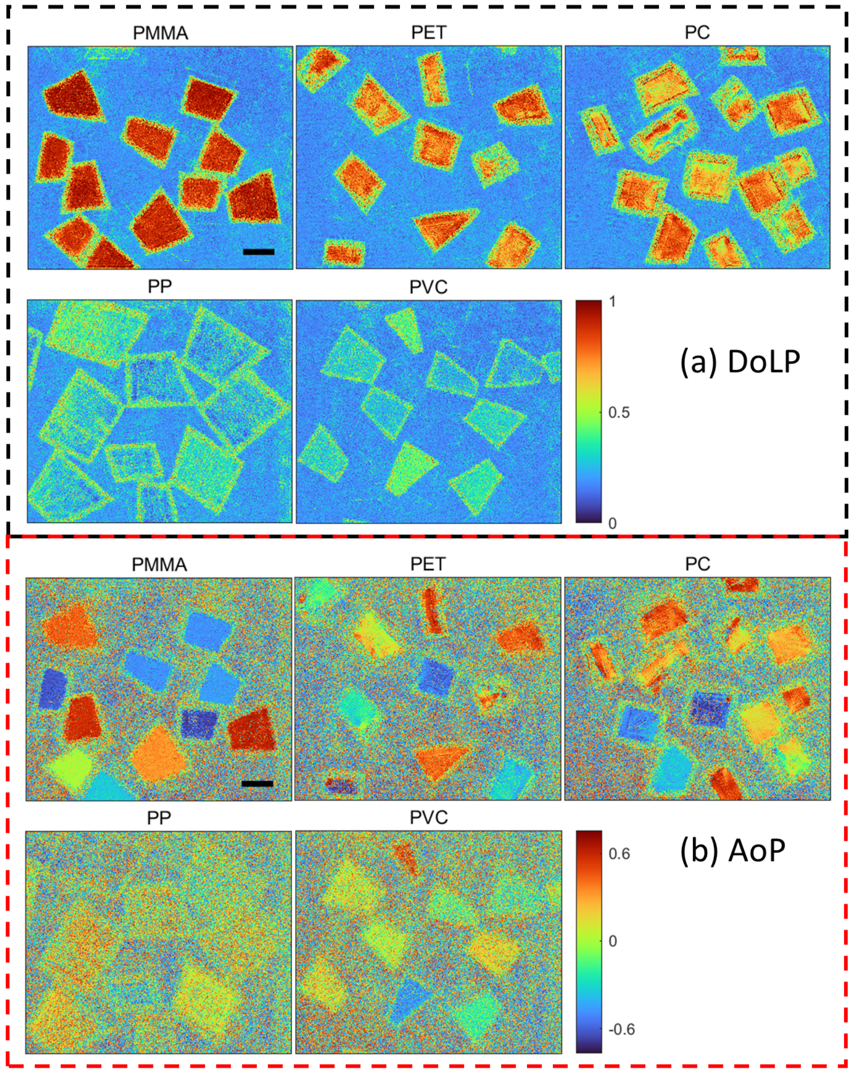


Figure 9: The color maps of DoLP and AoP for different MP samples. Scale bar: 1 mm.

rotation on the polarization maps, we conducted additional experiments where a typical PMMA particle was placed on a glass slide and manually rotated in both horizontal and vertical planes. The results demonstrate that the AoP map changes in response to particle rotation, while the DoLP map remains largely unaffected by particle rotation. It further indicates that DoLP is a robust feature that can effectively handle situations where MP particles are moving and rotating within a flow.

Quantitatively, the distributions of DoLP and AoP of different MP particles are statistically analyzed using boxplots. More than 100 particles are segmented using the proposed computational

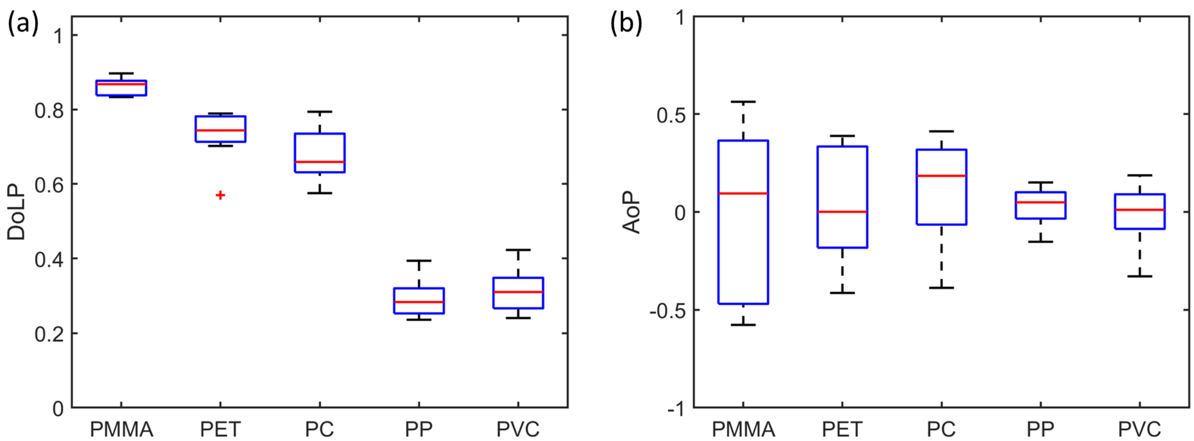


Figure 10: Visualization of the (a) DoLP and (b) AoP distributions of different MP samples using boxplots. The central red lines indicate the median and the horizontal blue edges of the box are the $25th$ and $75th$ percentiles.

method. As illustrated in Fig. 10, the central red line is the median. On one hand, since the AoP value of MP particles will be influenced by the optical axis angle of the particle, the statistical results of AoP show similar median values around zero. On the other hand, DoLP shows a significant difference among PMMA, PET, PC, and PP/PVC. Thus, an effective and reasonable screening criteria can be established based on DoLP. Nevertheless, PP exhibits a similar DoLP distribution with PVC, indicating that the two types of MP materials have similar birefringence properties. Additional information should be introduced to further distinguish PP from PVC.

Finally, evolution of DoLP of PMMA, PET, PVC particles, and the background, as a function of the media's optical depth, are shown in Fig. 11. In each case, the mean value of DoLP is calculated with more than 20 particles. The optical depth of the scattering media is defined as log-ratio between the transmitted ballistic photons and the incident photons.[42] The larger optical depth represents the stronger scattering effect of light when it is transmitted through the media. The measurement method of the optical depth is consistent with the reference.[42] It can be seen that the DoLP of the background increases slightly from 0.13 to 0.19, as the optical depth increases from 0 to 3.23. Meanwhile, the DoLP of three MP materials gradually decreases due to the depolarization effect of multiple scattering.[58] When the optical depth is less than 2.5, it is still possible to distinguish the three types of MP materials based on their DoLP features with turbidity cali-

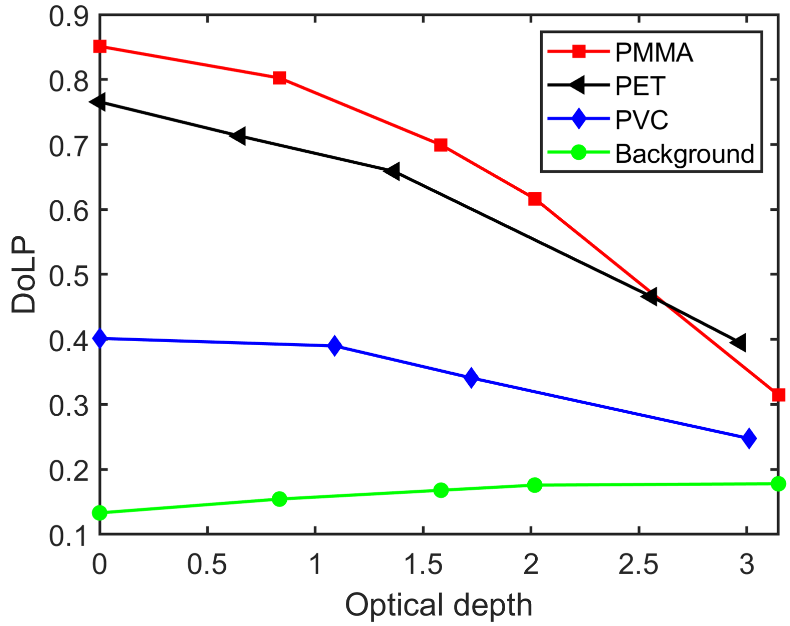


Figure 11: Evolution of DoLP of PMMA, PET, PVC particles, and the background, as a function of the media's optical depth.

bration. However, if the turbidity of the aqueous phase is extremely high (i.e., the optical depth is larger than 2.5), it is required to reduce media's turbidity or perform polarization compensation before MP particle classification.

Conclusions and future work

In summary, a hybrid compact imaging system based on in-line holography and snapshot polarization imaging is developed for *in situ* characterization and identification of MP particles. Particularly, a computational method based on polarization parameters is proposed to boost its detection capability in turbid water. As demonstrated in the proof-of-principle experiments, this imaging system is capable of obtaining comprehensive information about MP particles with the advantages of flexible refocusing, high-throughput analysis, and low-cost field-portable devices. Not only can the characteristics of MPs in shape, size, amount, and 3D location be quantitatively analyzed, but also the intrinsic birefringence properties can be resolved with the DoLP and AoP features. Compared with traditional intensity-based features, our polarization-related features offer much more resistance to scattering media. Furthermore, the capability of identifying MPs from microorganisms and classifying different types of MP materials is validated. It is demonstrated that AoP is a robust feature for accurate particle segmentation because it maintains remarkably consistent even in strongly scattering media. Additionally, the results indicate that DoLP is an angle-independent feature for distinguishing randomly dispersed MP particles. The classification of PMMA, PET, and PVC based on DoLP can be guaranteed when the media's optical depth is less than 2.5. Therefore, the resulting portable imaging system has significant potential for broad-scale and long-term monitoring of MP pollution in natural aquatic environments.

It is worth pointing out that the presented work aims to achieve *in situ* detection of MP particles with a portable imaging device. As a remarkable contribution of this work, the integrated imaging system with the corresponding computational method is indeed an effective solution to address the problem of MP detection in turbid water, without significantly increasing the complexity of the optical configuration. In particular, it is demonstrated that DoLP and AoP are unique features for imaging through scattering media and characterizing MP's intrinsic structure and material.

Nevertheless, it is important to acknowledge that real environmental MP samples are more complex, and realistic detection conditions are extremely heterogeneous. Therefore, it is evident that no single feature or method can handle all situations effectively. Instead, the proposed method should be viewed as a valuable collaboration with existing methods, rather than a complete replacement. Continuous efforts should be devoted to the development of MP monitoring systems in the future. For example, to ensure a comprehensive understanding of the transformations that MPs undergo in natural environments, it is imperative to collect and test more realistic aging MP samples that have been subjected to the effects of aging processes, shear stress, and salinity. More distinguishable features[53,55] could be extracted from the polarization-resolved holograms which contain abundant information about MP particles. In addition to manual feature selection, artificial intelligent methods[22,27] could be utilized to extract intrinsic features from the images. To enhance the practical applicability of our technique, it is crucial to explore the influence of various non-material factors, such as the color, size, thickness, and surface characteristics of MPs, on the classification metrics. Faced with low-visibility aquatic environments, photon-starved snapshot holography[59] using a quanta image sensor could be considered as a potential solution. Additionally, for identifying opaque MP samples, a reflective imaging modality based on the proposed method could be developed. Overall, it is believed that advanced optical approaches combined with appropriate computational methods hold great potential for addressing the challenge of severe MP pollution.

Funding Sources

The work is supported in part by the Research Grants Council of Hong Kong (GRF 17201620, RIF R7003-21). This work is partly funded by the Hong Kong Scholars Program (XJ2022032).

Acknowledgement

Jianqing Huang appreciates the partial financial support from Shanghai Jiao Tong University.

Author declarations

The authors declare no conflicts of interest.

Author contributions statement

J. H.: writing (original draft), writing (review and editing), sample preparation, experiments performing, formal analysis; Y. Z.: writing (review and editing), sample preparation, experiments performing; Y. L.: writing (review and editing), sample preparation, experiments performing; E. Y. L.: writing (review and editing), resources, supervision, funding acquisition.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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