

Three-dimensional Integral Imaging Visualization in Scattering Medium with Active Polarization Descattering

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Abstract: We present an integral image-based polarization descattering for underwater object visualization. Reconstruction based on integral imaging reduces noise and improves the estimation of the intermediate parameters required for polarization-based image recovery.

1. Introduction

Optical sensing and imaging methods are strongly challenged by absorption and scattering and underwater occlusion [1-3]. In turbid environments, the background and target region are hard to identify, thus hindering the estimation of the intermediate parameters (degree of polarization (DoP) of signal and background) required for polarization-based image recovery [4,5]. The three-dimensional (3D) reconstruction algorithm based on integral imaging reduces the noise and improves the estimation of the intermediate parameters required for polarization-based image recovery.

Integral imaging reconstruction combines multiple perspectives to provide spatial and depth information about the scene [6]. The degradation in turbid water can be modeled as $I = D(x, y) + B(x, y)$, where $D(x, y)$ is the target light and $B(x, y)$ is the background light [4,5]. Two orthogonal components can expand to a polarized component of the target ($D_{\parallel}(x, y)$ and $D_{\perp}(x, y)$) and background ($B_{\parallel}(x, y)$ and $B_{\perp}(x, y)$). The target light can be calculated as [4]

$$\hat{D}^{rec}(x, y) = \frac{1}{\hat{P}_{scatt} - \hat{P}_{obj}} [I_{\perp}^{rec}(x, y) * (1 + \hat{P}_{scatt}) - I_{\parallel}^{rec}(x, y) * (1 - \hat{P}_{scatt})] \quad (1)$$

Where $\hat{D}^{rec}(x, y)$ represent estimated target object after removal of the estimated backscatter. $I_{\parallel}^{rec}(x, y)$ and $I_{\perp}^{rec}(x, y)$ are the 3D integral imaging reconstructed, co-polarized image and cross-polarized image with respect to transmitted signal polarization. To estimate P_{scatt} , we selected the background region Ω of the 3D reconstructed image

$\hat{P}_{scatt} = \frac{\sum_{\Omega} I_{\parallel}^{rec}(x, y) - \sum_{\Omega} I_{\perp}^{rec}(x, y)}{\sum_{\Omega} I_{\parallel}^{rec}(x, y) + \sum_{\Omega} I_{\perp}^{rec}(x, y)}$ Similarly, the estimation of the degree of the polarization of signal light P_{obj} can be

calculated by selecting the signal region Ψ of the 3D reconstructed image $\hat{P}_{obj} = \frac{\sum_{\Psi} I_{\parallel}^{rec}(x, y) - \sum_{\Psi} I_{\perp}^{rec}(x, y)}{\sum_{\Psi} I_{\parallel}^{rec}(x, y) + \sum_{\Psi} I_{\perp}^{rec}(x, y)}$ [4].

$\hat{D}^{rec}(x, y)$ represent estimated target object after removal of the estimated backscatter. We propose a polarimetric multidimensional integral imaging-based experimental setup for underwater data collection in a turbid and occluded environment. The experimental setup is shown in Fig. 1(a)

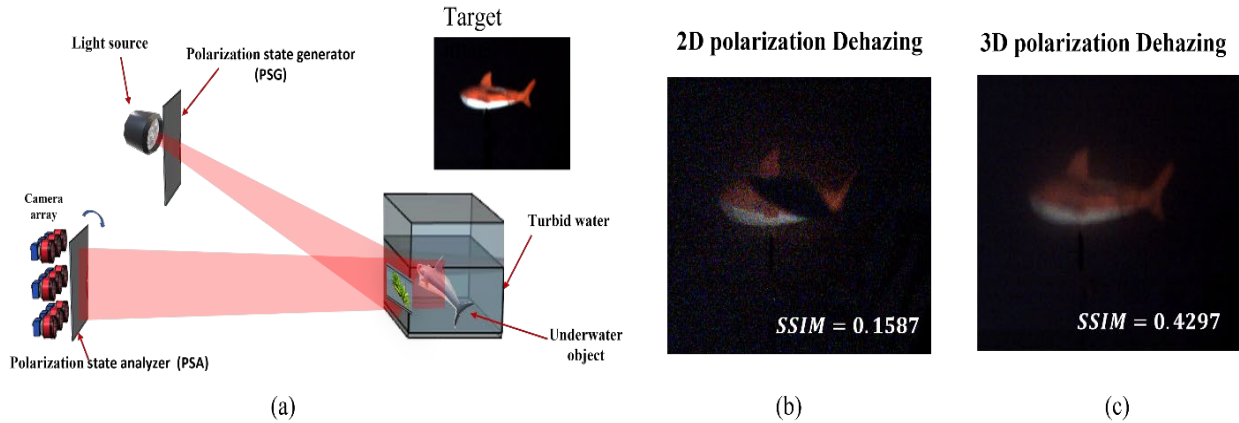


Fig. 1(a). Experimental setup for underwater optical signal detection. The linear polarizer serves as the polarization state generator (PSG) placed in front of an LED light source emitting red light to provide polarized illumination. At the receiver end, a linear polarizer is used as a polarization state analyzer (PSA) in front of the camera array to capture the polarimetric information of the scene. (b) An example of the underwater object with partial occlusion viewed from the central camera perspective, taken at Beer's coefficient $\alpha = 0.0116 \text{ mm}^{-1}$, and (c) an example of a reconstructed image using 3D integral imaging with occlusion at $\alpha = 0.0116 \text{ mm}^{-1}$.

The test data was collected in the turbid and partially occluded environment using the same experimental setup shown in Figure 1(a). Six different turbidity levels were recorded, ranging from $\alpha = 0.0041$ to 0.0213 mm^{-1} . For the 3D experiment, each recorded test data was enhanced using integral imaging-based polarization dehazing at focus depth plane of target object. Example test data images have been shown in Fig. 1(b) and 1(c). We used structure similarity index measure (SSIM) to analyze the images. SSIM is a metric that quantifies the similarity of two images [7]. It can be calculated as $SSIM = (\mu_x \mu_y + c_1)(2\sigma_{xy} + c_2) / ((\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2))$, where x and y are the original image and the reconstructed image respectively [7]. μ_x and μ_y are the mean values of x and y , respectively. σ_x^2 and σ_y^2 are the variances of the pixel intensity in the corresponding images. σ_{xy} is the covariance of the pixel intensity in both images and c_1 and c_2 are regularization parameters to avoid dividing zero. For SSIM calculation, reference image is the clear water image without occlusion. The central perspective elemental image is the same as conventional 2D imaging. These SSIM values at various turbidity levels are reported in Table 1.

Table 1. Structural Similarity Index (SSIM) at various turbidity levels for 2D imaging and 3D integral imaging.

Beer's Coefficient (α)	Structural Similarity Index (SSIM)	
	2D polarization Dehazing	3D InIm polarization Dehazing
0.0041	0.2856	0.6818
0.0075	0.2389	0.5488
0.0116	0.1587	0.4297
0.0184	0.1182	0.3614
0.0213	0.0737	0.3085

InIm: Integral imaging

From Table 1, we can see that the proposed 3D InIm dehazing achieves a significant performance improvement as compared to conventional 2D imaging for the experimental settings considered in this manuscript.

2. Conclusion

In conclusion, we have presented a 3D polarization dehazing-based detection method in the turbid and occluded medium. We compared the proposed method's performance to that of traditional 2D imaging and CNN-BiLSTM -based techniques. Our experimental results indicate that the 3D integral-based proposed method may substantially improve the performance of optical signal detection compared to other imaging modalities under degraded environments such as partial occlusion and turbidity. Future experiments might include detection in more challenging environments such as underwater turbulence [8], low light intensity, multipath fading channels, and exploring other integral imaging architectures. B. Javidi acknowledges support from the Air Force Office of Scientific Research (FA9550-21-1-0333); Office of Naval Research N000142212375, N00014-20-1-2690, N000142212349; and National Science Foundation 2141473.

References

- [1] G. Krishnan, R. Joshi, T. O'Connor, and B. Javidi, "Optical signal detection in turbid water using multidimensional integral imaging with deep learning," *Opt. Express* 29, 34035–34050 (2021).
- [2] R. Joshi, G. Krishnan, T. O'Connor, and B. Javidi, "Signal detection in turbid water using temporally encoded polarimetric integral imaging," *Opt. Express* 28, 36033–36045 (2020).
- [3] R. Joshi, T. O'Connor, X. Shen, M. Wardlaw, and B. Javidi, "Optical 4D signal detection in turbid water by multidimensional integral imaging using spatially distributed and temporally encoded multiple light sources," *Opt. Express* 28(7), 10477–10490 (2020).
- [4] T. Treibitz and Y. Y. Schechner, "Active polarization descattering," *IEEE Transactions on Pattern Analysis and Machine Intelligence* 31(3), 385–399 (2009).
- [5] M. Dubreuil, P. Delrot, I. Leonard, A. Alfalou, C. Brosseau, and A. Dogariu, "Exploring underwater target detection by imaging polarimetry and correlation techniques," *Appl. Opt.* 52(5), 997–1005 (2013).
- [6] G. Lippmann, "Épreuves réversibles donnant la sensation du relief," *J. Phys. Theor. Appl.* 7(1), 821–825 (1908).
- [7] Wang, Z., Bovik, A. C., Sheikh, H. R., Simoncelli, E. P. "Image quality assessment: from error visibility to structural similarity". *IEEE transactions on image processing*, 13(4), 600-612 (2004).
- [8] Z. Vali, A. Gholami, Z. Ghassemloooy, M. Omooni, and D. G. Michelson, "Experimental study of the turbulence effect on underwater optical wireless communications," *Appl. Opt.* 57(28), 8314–8319 (2018).