Correspondence imaging through scattering media

Zhihan Xu and Wen Chen*
Department of Electrical and Electronic Engineering
The Hong Kong Polytechnic University,
Hong Kong, China
*Email: owen.chen@polyu.edu.hk

ABSTRACT

Correspondence imaging (CI) realizes object reconstruction by conditionally averaging random patterns with a constant threshold which is generated from light intensities recorded by a single-pixel detector. However, object reconstruction in CI meets its challenge in complex media where the recorded light intensities fluctuate due to scaling factors existing in the optical channel. In addition, CI suffers from low quality because of conditional averaging among random patterns. In this paper, we report a varying-threshold-based CI that enables object reconstruction with high quality through complex media. To eliminate effect of dynamic scaling factors caused by complex media, varying thresholds are estimated by building an optimization model to optimize consistency between the estimations and light intensities. Then, the estimated varying thresholds can be utilized to binarize light intensities. In addition, to improve reconstruction quality, an optimization model is built by minimizing the L1 norm and total variation (TV) norm. We demonstrate the method using optical experiments. It is verified that the method can eliminate the effect of dynamic scaling factors and realize object reconstruction with high quality.

Keywords: Correspondence imaging, Complex media, Varying thresholds, Optimization.

1. INTRODUCTION

Imaging through scattering media meets its challenge when scattering media become complex [1–3]. To eliminate the effects, conventional imaging systems based on pixelated detectors might require complicated designs [4,5] or tedious post-processing [6,7], hindering their applications in real environments. Ghost imaging (GI) is an emerging computational imaging scheme where a series of illumination patterns are projected onto a target and light intensities are recorded by a single-pixel detector [8–11]. By correlating illumination patterns and light intensities, GI enables imaging with high robustness, wide spectrum and quick response [12–14]. In addition, compared with conventional imaging systems, GI is robust to scattering effect with simple setups and efficient algorithms [15,16].

Correspondence imaging (CI) has found applications across diverse fields. Instead of performing cross-correlation in GI, recorded light intensities are binarized with a constant threshold, which divides associated illumination patterns into two categories [17]. By superimposing illumination patterns within the same category, object reconstruction can be conducted, called as positive image and negative image [18]. An object reconstruction with a higher contrast can be realized by subtracting negative image from positive image, called as a differential image. Compared with GI, CI features higher efficiency in data storage, transmission and higher robustness to non-linear effect during measurements [19]. However, few work about CI focuses on object reconstruction through complex media since binarizations based on a constant threshold cannot correct light intensities.

A varying-threshold-based CI is reported here to realize object reconstruction through complex scattering media. To estimate varying thresholds to eliminate effect of dynamic scaling factors, an optimization model is built to optimize consistency between estimated varying thresholds and recorded light intensities. Then, the estimated varying thresholds are used to binarize light intensities. Another optimization model is built to achieve object reconstruction with high quality via minimizing L1 Norm and total variation (TV) norm. Optical experiments are conducted to verify that the method can remove the effect of dynamic scaling factors and realize object reconstruction with high quality.

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2. METHODOLOGY

In CI through complex media, a series of random patterns $P_i(x, y),\ i = 1, \cdots, m,$ are projected onto an unknown object $O(x, y)$ with optical waves propagating through complex media. A single-pixel detector is utilized to measure light intensities, described by [20]

$$\tilde{s}_i = k_i s_i = k_i \sum_x \sum_y P_i(x, y) \cdot O(x, y), \tag{1}$$

where s_i denotes light intensities recorded in free space without scattering media, $\tilde{s}_i$ denotes light intensities recorded through complex scattering media with dynamic scaling factors k_i in an optical path, and (x, y) represents 2-D spatial coordinate. It is worth noting that dynamic scaling factors k_i caused by complex media oscillate, which cannot be removed in conventional CI.

To eliminate effect of dynamic scaling factors k_i, statistical property of light intensities $\tilde{s}_i$ should be utilized. It has been demonstrated that light intensities recorded through complex scattering media should be Gaussian-distributed [18] described by

$$p(\tilde{s}_i) = \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{(\tilde{s}_i - \mu_i)^2}{2\sigma_i^2}}, \tag{2}$$

where μ_i and σ_i denote expectation and standard deviation, respectively. The statistical property of light intensities $\tilde{s}_i$ can be used as a *prior* to estimate parameters $\hat{\mu}_i$ as varying thresholds and then eliminate effect of dynamic scaling factors. Hence, an optimization model is built to optimize data consistency described by [20]

$$\hat{\mu}_i, \sigma_i = \arg\max \sum_{i=1}^{m} \log\left(\frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{(\tilde{s}_i - \mu_i)^2}{2\sigma_i^2}} \right), \tag{3}$$

where $\hat{\mu}_i$ and $\hat{\sigma}_i$ denote optimized parameters. Then, $\hat{\mu}_i$ can be used as estimated varying thresholds to binarize the recorded light intensities $\tilde{s}_i$.

An optimization model is further built to minimize L1 norm and total variation (TV) norm described by [20]

$$\hat{O}(x, y) = \arg \min_{\|O(x,y)\|_2 \le 1} \left\{ -\left[\sum_{i=1}^{m} \left(\sum_x \sum_y P_i(x, y) \cdot O(x, y) \right) \cdot \tilde{s}_i^{(\pm)} \right] + \lambda_1 \|O(x, y)\|_1 + \lambda_2 \|O(x, y)\|_{TV} \right\}, \tag{4}$$

where $\tilde{s}_i^{(\pm)}$ represents the binarized light intensities, and λ_1 and λ_2 denote regularization parameters. The optimization model in Eq. (4) can be carried out by performing L1 minimization and TV minimization, which generates a high-quality object image $\hat{O}(x, y)$.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Experimental setup is shown in Fig. 1. A digital light projector (Texas Instruments, DLP4710EVM-LC) projects a series of random patterns with 128 ×128 pixels onto an object. It is worth noting that sampling ratio in this experiment is set to be 1.0. Optical wave propagates through a complex scattering medium which is generated by continuously dropping 200-ml milk solution (combination of 150-ml clean water and 50-ml milk) into a transparent water tank with dimensions of 10.0 cm (length) ×20.0 cm (width) ×30.0 cm (height). During the experiments, an electrical stirrer keeps rotating at 400.0 rpm. The light field is focused by a lens with a focal length of 10.0 cm and collected by a single-pixel detector (Thorlabs, PDA100A2).

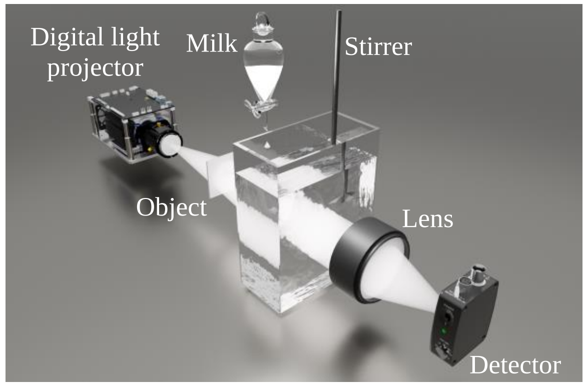

Figure 1. A schematic experimental setup.

The recorded light intensities and associated random patterns can be fed into optimization models in Eqs. (3) and (4) to estimate varying thresholds and perform object reconstruction. Light intensities recorded through complex scattering media are shown in Fig. 2(a) with varying thresholds estimated by solving the optimization model in Eq. (3). It can be observed that the estimated varying thresholds can match the overall tendency of the recorded light intensities. Then, the recorded light intensities are binarized by the estimated varying thresholds with associated random patterns divided into two categories. Figures 2(b) and 2(c) show positive image and negative image by superimposing random patterns within each category. An object reconstruction with a higher contrast can be conducted by subtracting the negative image from the positive image, as shown in Fig. 2(d). It should be noted that object reconstructions in Figs. 2(b)–2(d) still suffer from low quality. To improve reconstruction quality, the optimization model in Eq. (4) is applied, and the result is shown in Fig. 2(e).

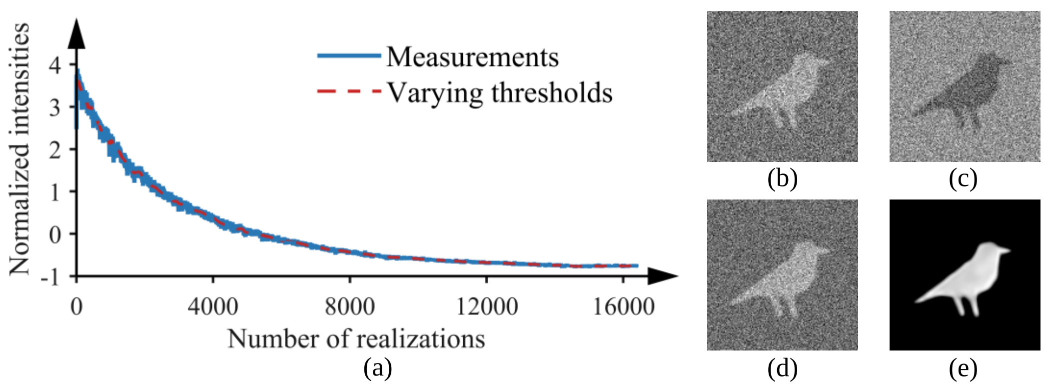

Figure 2. Experimental results: (a) Recorded light intensities and estimated varying thresholds, (b)-(d) positive image, negative image and differential image, and (e) object reconstruction via solving the optimization model in Eq. (4).

4. CONCLUSION

Varying-threshold-based CI is reported to realize high-quality object reconstruction through complex scattering media. To eliminate effect of dynamic scaling factors, an optimization model is built by optimizing consistency between estimated varying thresholds and light intensities. Then, the estimated varying thresholds are utilized to binarize the light intensities. Another optimization model is built to perform object reconstruction with high quality by minimizing L1 norm and TV norm. It is verified that the method can remove the effect of dynamic scaling factors and realize high-quality object reconstruction. Future works may focus on implementing varying-threshold-based CI at ultra-low sampling ratios to achieve sensing for complex scenes.

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