Speckle Imaging through Scattering Layers

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***Abstract*—This report explores the emerging field of speckle imaging as a real-time non-invasive technique to overcome the challenges associated with optical imaging through scattering layers, such as biological tissues. Traditional model-based reconstruction methods face significant limitations due to their reliance on assumptions about the medium's optical properties and susceptibility to noise, which can compromise imaging performance. As an alternative, speckle imaging leverages specific characteristics of the scattering medium, particularly memory effects, to represent the complex light propagation process through a low-dimensional framework. This approach allows for effective image reconstruction without requiring exhaustive physical modeling. The report compiles a review of critical and recent publications on speckle imaging, with discussions on key advancements in large field-of-view, super-resolution imaging, and object tracking. Furthermore, it presents a reproduction study detailing a basic speckle imaging technique, illustrating its practical efficacy. Concluding with a discussion on the advantages, limitations, and future prospects of speckle imaging, this report highlights the technique's potential for revolutionizing imaging through scattering media in various scientific and engineering applications.**

***Index Terms*—Non-invasive imaging, Scattering layers, Model-based reconstruction, Speckle imaging, Memory effects.**

I. Introduction

Non-invasive imaging through scattering layers, such as biological tissues, offers potential advantages for a variety of engineering and research fields. However, the inherent inhomogeneity of a scattering medium leads to light scattering, which morphs any optical beam into a complex speckle pattern, thereby limiting the resolution, depth and speed of optical imaging.

A promising strategy for imaging through scattering layers involves model-based reconstruction. This approach employs mathematical or computational models of light propagation to anticipate the light distribution within the scattering medium. These models, typically based on the radiative transport equation or its diffusion approximation, take into account the optical properties of the medium, such as absorption and scattering coefficients. The collected data, typically the scattered light's intensity, is then compared with the model's predictions. And an inversion algorithm progressively adjusts the model parameters until the predictions correspond with the collected data, thus enabling the reconstruction of images hidden target.

However, model-based methods pose three challenges. Firstly, they rely on assumptions about the underlying physics and the properties of the scattering media. For instance, the diffusion equation assumes isotropic scattering, i.e. equally probable in all directions. Nevertheless, in some types of tissues, scattering might be anisotropic or direction-dependent. When the model does not accurately describe the physical process, the imaging performance is undermined. Secondly, model-based methods often necessitate an estimation or initial guess of parameters related to the medium's optical properties. These parameters generally require pre-calibration, which may not always be feasible in practical applications. Finally, the methods can be negatively affected by measurement noise in the data, further degrading the quality of the reconstructed images.

An alternative to model-based methods is speckle imaging. Instead of striving to accurately depict the physical process of light propagation, speckle imaging is tailored for specific instances where the scattering medium exhibits unique characteristics, particularly memory effects. Even though these features do not thoroughly describe the complete physical process within the scattering medium, they offer a low-dimensional representation of the high-dimensional physical process. And heuristic algorithms based on these features can accurately and effectively resolve the issue.

This report reviews several key and recent publications on real-time non-invasive speckle imaging through scattering layers. The report is structured as follows: Part II introduces the principle and setup of imaging through a scattering medium. Part III reviews recent advancements in the field, such as large field-of-view, super-resolution imaging, and object tracking. Part IV showcases a reproduction process and results of a basic speckle imaging technique through scattering layers. Finally, Part V discusses the advantages, disadvantages, and potential future applications of this technique.

II. Principle

A schematic of the experiment for imaging through a scattering medium, as well as a numerical example, are presented in Fig. 1. An object is hidden at a distance behind a highly scattering medium. For mathematical convenience, we assume that the object is illuminated by a spatially incoherent, narrow-band source, and a high-resolution camera that is placed at a distance on the other side of the medium records the pattern of the scattered light that has diffused through the scattering medium. Since the raw recorded camera image is a low-contrast, random and seemingly information-less image (Fig. 1b), we are going to obtain the object's image from its autocorrelation.

One essential observation is that the autocorrelation of the diffused light is essentially identical to the object's autocorrelation, which is the intrinsic isoplanatism that arises from the angular 'memory effect' for speckle correlation. Simply put, the memory effect states that light from nearby points on the

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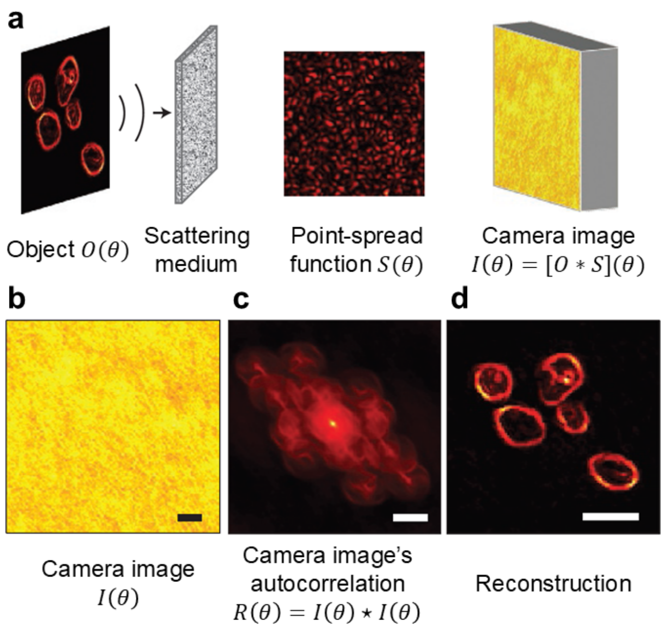

Fig. 1. Non-invasive imaging through strongly scattering layers by speckle correlations: concept and numerical example. a, Experimental set-up. An object (a group of organelles in the numerical example) is hidden behind a visually opaque scattering medium. The object is illuminated by a spatially incoherent narrowband source and a high-resolution camera records the scattered light pattern on the other side of the scattering medium. b, Raw camera image, $I(\theta)$. Within the memory-effect range32, this image is given by a convolution of the object intensity pattern $O(\theta)$ with a random speckle pattern $S(\theta)$. c, The autocorrelation of the seemingly information-less raw camera image, $R(\theta)$, is essentially identical to the object's autocorrelation (c) as a result of the sharply peaked autocorrelation of the speckle pattern. d, The object's image is obtained from the autocorrelation of b by an iterative phase-retrieval algorithm. Scale bars: 30 camera pixels

object is scattered by the diffusive medium to produce highly correlated, but shifted, random speckle patterns on the camera. Points at the object plane that lie at a distance that is within the memory-effect range generate nearly identical speckle patterns on the camera. These patterns are shifted with respect to one another on the camera plane by a relative distance. For spatially incoherent illumination (as well as for fluorescence emission) no interference takes place between the different patterns and the camera image is simply a superposition of these identical shifted speckle intensity patterns. This therefore allows the system of Fig. xxx to be viewed as an incoherent imaging system with a shift-invariant point-spread function (PSF) that is equal to the random speckle pattern. The complex camera image, $I(\theta)$, is then given by a convolution of the object intensity pattern $O(\theta)$ with this PSF:

$$I(\theta) = O(\theta) * S(\theta) \tag{1}$$

Here, the symbol $*$ denotes a convolution operation, $S(\theta)$ represent the random speckle pattern. Taking the autocorrelation of the complex camera image and using the convolution theorem yields:

$$\begin{aligned} R(\theta) &= I(\theta) \star I(\theta) \\ &= [O(\theta) * S(\theta)] \star [O(\theta) * S(\theta)] \\ &= [O(\theta) \star O(\theta)] * [S(\theta) \star S(\theta)] \end{aligned} \tag{2}$$

Here, $R(\theta)$ denotes the autocorrelation of the complex camera image, $\star$ denotes the autocorrelation operation. As the autocorrelation of the random speckle pattern, $(S * S)$, is a sharply peaked function (essentially the autocorrelation of broadband noise), the righthand side of equation xxx is effectively equal to the autocorrelation of the object's image $O(\theta) \star O(\theta)$. The autocorrelation can be computed from the magnitude of the complex camera image via Wiener–Khinchin:

$$R(\theta) = \mathcal{F}^{-1}\{|I(\theta)|^2\} = O(\theta) \star O(\theta) \tag{3}$$

What we need to do is to solve the object's image $O(\theta)$ from the captured camera image $|I(\theta)|$, thus the problem is essentially a phase retrieval problem. Many algorithms can be applied to solve this problems.

Although the vanilla speckle imaging scattering layers achieves non-invasive real-time high-resolution imaging. Several conditions should be met in order to allow high-fidelity imaging with the presented technique. For example, the object's angular dimensions, as seen through the random medium, must be smaller than the memory-effect range (the FOV). As a result, similar to other memory-effect-based techniques the approach is effective when the object's distance from the scattering layer is considerably larger than the effective layer thickness. Wide-field imaging inside thick, multiply-scattering tissue still presents a challenge.

III. Advancement

The Vanilla Method offers a groundbreaking approach for optical imaging of fluorescent objects obscured by opaque scattering layers, attaining a spatial resolution of 10 μm. Conventional optical techniques often grapple with imaging through scattering layers that distort light and obscure objects behind them. To address this issue, the authors utilize a non-invasive approach that harnesses laser illumination and speckle correlations to capture the hidden object's fluorescence. This method involves scanning the angle of incidence of a laser beam through the scattering layer and measuring the emitted fluorescence. This information is then used to construct an image of the hidden object through an iterative algorithm. This technique has successfully produced high-resolution images of objects, such as biological samples, despite the presence of diffusers that would typically hinder visualization. This novel approach bears potential applications across various disciplines requiring precise imaging through scattering media, marking a significant advancement in non-invasive optical imaging technology.

A recent method attempts to address the challenge of non-invasive, single-shot imaging through scattering media using the memory effect for speckle correlations. However, this method is primarily limited by its restricted field of view (FoV) and spatial resolution, due to the angular range of the optical memory effect. The FoV of the Vanilla Method is approximately 1 mrad, with a spatial resolution of around 0.5 mm. In contrast, a new technique introduced in a recent paper overcomes this FoV limitation by employing variable random illumination and matrix factorization to separate fluorescent signals. This enables fluorescence imaging through scattering layers over an FoV that greatly exceeds the constraints of the memory effect, eliminating the need for wavefront shaping or precise knowledge of the scattering medium. This innovation enhances non-invasive imaging capabilities, providing a robust and flexible approach suitable for various incoherent contrast mechanisms and illumination schemes. The spatial resolution of this random illumination method reaches 1 μm.

Another solution to the FoV problem is found in the context of dynamic scattering environments or applications. The Dynamic Method introduces the Stochastic Optical Scattering Localization Imaging (SOSLI) technique, which surpasses the diffraction limit by capturing multiple speckle patterns from photo-switchable point sources. This enables super-resolution imaging with a resolution of up to 100 nm, even through dynamic scattering media like biological tissues. Utilizing speckle correlation properties, SOSLI achieves an eight-fold improvement in resolution beyond the diffraction limit in both static and dynamic environments. This allows for detailed imaging of structures at a nanometer scale, a feat unattainable with the Vanilla Method.

Moreover, the method of introducing movable objects enables high-resolution reconstruction and tracking of moving objects through scattering media using speckle correlations, with minimal computational effort. This real-time technique effectively tracks motion beyond the memory effect range, offering a practical solution for dynamic scenarios where rapid changes occur. By exploiting speckle correlations between frames without the need for complex inversion algorithms, the movable object method efficiently determines object motion. This method overcomes the computational and dynamic application limitations of the Vanilla approach.

A recent paper introduces the innovative imaging method "speckle kinetography." This approach tackles the significant challenge of optical imaging in scattering media, which is vital for fields like biomedicine and astronomy. Unlike traditional methods, which are limited by prior knowledge of the sample or medium-dependent properties, this technique uses an overlapping speckle correlation algorithm to extract detailed information from incoherent speckle images of moving objects. This process enables the construction of an object's autocorrelation, achieving high-resolution imaging up to 1 μm even in unknown media as thick as six transport mean free paths. Demonstrations under various illumination conditions, including LED, white light, and fluorescence, underscore its versatility and potential broad applicability. This advancement could revolutionize imaging scenarios where traditional methods falter, offering a non-invasive, high-resolution alternative without the need for detailed media characterization.

IV. Experiments

We have reproduces the code of large FoV method by involving a meticulous recreation of their innovative imaging methodology.

We acquired the relevant data sets and the complete reconstruction code available from the speckimg GitHub repository, which was instrumental in accurately duplicating the experimental results. Our approach commenced with leveraging Non-negative Matrix Factorization (NMF) to demix the speckle images, allowing us to reconstruct high-quality images that transcended the typical field of view limitations imposed by the optical memory effect. Crucially, the reconstruction code permitted us to execute the fingerprint-based reconstruction algorithm, unveiling detailed images of both widely spaced and continuous fluorescent objects such as beads and pollen grains. Testing the method across various sample types and scattering conditions confirmed the robustness and versatility of this non-invasive imaging technique, validating the paper's claims and exceeding the boundaries of conventional optical imaging methodologies by demonstrating field of view enhancements up to threefold the standard memory effect range.

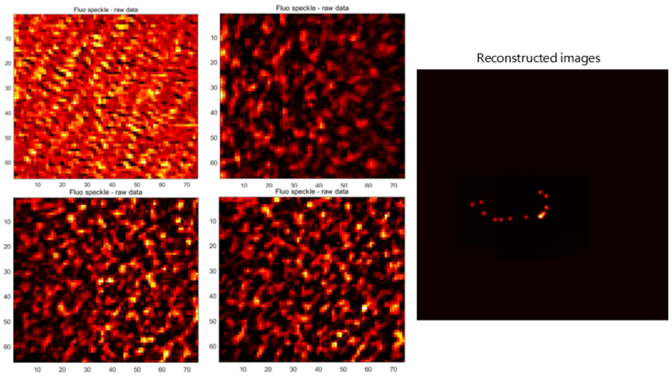

Fig. 2. Reproduced code and reconstructed images. left: the decomposed fingerprint image from random fluctuating illumination. right: the reconstructed image. Each paticle in this image is about 5 μm.

The results are illustrated in Figure 2, which depicts four distinct speckle patterns. These patterns were generated by applying a fingerprint-based reconstruction algorithm. Within the memory effects, the fingerprint image is nearly self-irrelevant, thereby producing an auto-correlation function that closely resembles a delta function. Conversely, for those fingerprint images that exist outside the memory effects, the auto-correlation image appears as a noise-like image. This unique property allows the use of fingerprints within the memory effects to reconstruct a high-resolution image of the target. This process is displayed in Figure 2. The application of the fingerprint-based reconstruction algorithm and the subsequent generation of speckle patterns provides a clear demonstration of how memory effects can be utilized in image reconstruction.

V. Discussion

The field of non-invasive imaging through scattering layers has made significant advancements in recent years. Despite this, its practical application remains limited for several reasons. Firstly, the real-time high-resolution imaging technique relies on speckle imaging, which struggles to address three-dimensional problems. Secondly, the strict requirements of random speckle on the scattering media are not consistently met. Nonetheless, there are potential methods to incorporate time-of-flight sensors or deep learning to manage more complex scenarios in this field.

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