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Imaging Inside Tissue Using Speckle Statistics

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Abstract: We exploit speckle intensity correlations to image incoherent illuminators inside scattering layers. Specifically, correlation properties of speckles created by near-field illuminators are used. Compared to previous far-field approaches, our approach achieves order-of-magnitude expansion in both the range and density of illuminators it can recover.

1. Introduction

Coherent light passing through participating media, such as biological tissue, scatters and produces noise-like images known as speckle. Despite their seemingly random nature, speckles have strong statistical properties such as the memory effect (ME), which means that speckle patterns produced under nearby illumination conditions are correlated shifted versions of each other. The ME can be used to enable imaging-through-scattering capabilities, such as the detection of incoherent illumination sources inside a highly-scattering layer, based on the observation that the auto-correlation of the observed speckle pattern and the unknown illuminators are equivalent [3]. Even though this observation and methodology carry great promise for tissue imaging, in practice, it has been limited due to three main reasons. First, the range of illuminators that can be recovered is strongly constrained by the limited range of the ME. Second, as the spatial density of sources increases, speckle contrast decays, severely limiting the density of recoverable sources—a constraint that has received less attention in the literature. Third, most previous experimental implementations use imaging conditions where the latent hidden sources are located in the *far field*, at a distance of at least a few centimeters behind the scattering layer. By contrast, biomedical applications are concerned with the detection of fluorescent light sources in the *near field*, inside tissue.

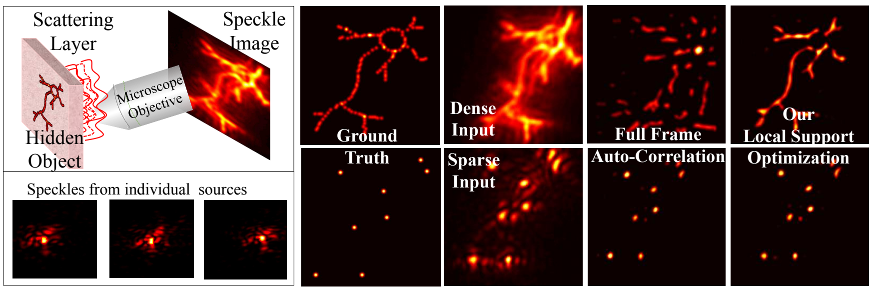

Fig. 1: We improve the classic full-frame algorithm by exploiting the local support of speckles (bottom left). Both algorithms are successful when the object is sparse (lower right). However, our approach can recover a much denser object (top right).

This article summarizes a new algorithm we introduced in [1], imaging through scattering layers using unique properties of the near-field problem. Our new algorithm detects light sources inside the scattering sample, significantly expanding their recoverable range and density compared to the original algorithm of [3].

2. Memory effect in the near field

Based on the physically-accurate speckle simulator of Bar et al. [2], we briefly introduce an analysis that will help us understand the extent of near-field correlations we can expect to have when developing our algorithm. We consider an imaging geometry where illuminators are located exactly on the back surface of a scattering sample, and a microscope objective images from its opposite side. We evaluate the translational correlation as a function of the displacement between two illuminators. We make three key observations.

Our first observation is that, as sample thickness increases, the maximum displacement at which significant correlation exists decreases. For non-zero displacement, correlation is present only for samples of low to medium optical depth, and thus ME-based imaging-through-scattering is practical only for such optical depths. This is still a useful setting for real applications, as it is considerably beyond the penetration depth of a standard microscope.

Our second observation is that, to increase correlation, we should set the distance of the microscope objective such that, in the absence of the scattering sample, it would focus exactly at the illuminators plane.

Our third observation is that, due to the strongly forward-scattering properties of tissue, light undergoing only few scattering events spreads over a small cone of directions. The resulting speckle patterns only cover a small region around the position of the illuminator producing them. Imaging with a focused objective further reduces the extent of this region. This *local support* property of speckle patterns is the basis for our imaging-through-scattering algorithm, which we describe next.

3. Imaging through scattering layers using local support

We consider the speckle *input image* I generated when a scattering sample is illuminated simultaneously by K *mutually-incoherent* illuminators $\mathbf{i}_k$. We denote the intensity of the speckle pattern each illuminator would produce independently as $I^{\mathbf{i}_k}(\mathbf{v})$. The captured speckle image is the incoherent superposition over all illuminators, $I(\mathbf{v}) = \sum_{k=1}^{K} I^{\mathbf{i}_k}(\mathbf{v})$. We denote by O the binary *latent image* that would be generated if there were no scattering sample, corresponding to the locations of all K illuminators. Assuming perfect ME, Katz et al. [3] argue that $I \star I \approx O \star O$. Using this property, the latent image can be recovered from the auto-correlation of the captured image using phase retrieval. We refer to this as the full-frame auto-correlation approach.

On the other hand, our algorithm takes advantage of the local support property of speckle patterns formed under near-field imaging setting. In particular, it works by matching the auto-correlation in *local windows* of the input image I, rather than over the entire image. Namely, if I_{w_j}, O_{w_j} are windows from the input and latent images, respectively, then we recover O by solving the optimization problem

$$\min_{O} \sum_j \|I_{w_j} \star I_{w_j} - O_{w_j} \star O_{w_j}\|^2, \tag{1}$$

where j sums over all windows. The full-frame auto-correlation approach becomes equivalent to the optimization problem of (1) if one uses a single window w_j of extent equal to the entire image. Our local approach has two main advantages compared to the full-frame one: First, as we analyze [1], it significantly increases the signal-to-noise ration (SNR) of the detected correlation. Since the speckles contributed from a single illuminator spread only over a local window around it, summing speckle at pixels outside this window only adds noise rather than correlated signal. Second, the full-frame cost requires that the ME holds between every pair of illuminators. Our cost uses multiple local windows w_j such that the ME is only required between illuminators inside each local window, rather than the entire frame. In our implementation, we solve the optimization problem of (1) using gradient-descent.

Results. To test our approach, we use chicken breast slices of thickness $[100-150]\mu m$ as scattering samples. We image spatially-incoherent sources at the back surface of the samples, using a focused microscope objective placed at the front surface. The reconstruction produced by our local approach significantly outperforms the results of the full-frame approach (Figs. 1–2). We also show experiment results for varying densities of latent illuminators. The largest density for which the full-frame approach succeeds is significantly smaller than that of our local correlation approach. This demonstrates that the SNR improvement offered by our local approach can significantly increase the density of illuminator patterns that we can recover. In [1] we also show that our local approach is helpful for expanding the extent of recoverable illuminator patterns, and in particularly that it can successfully reconstruct patterns with extent much larger than the maximum displacement at which the ME holds.

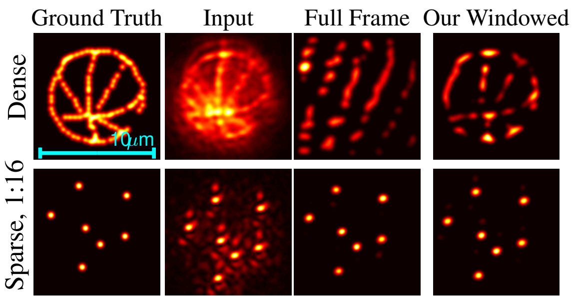

Fig. 2: The full-frame approach fails unless provided a considerably sparser input.

References

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