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Computational fluorescence imaging with multi-core fiber bundles – Towards high-speed imaging through bare optical fibers.

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Wavefront control of the coherent lasers has opened a new class of imaging techniques through optical fibers called lensless endoscopes. A spatial light modulator (SLM) at the entrance of an optical fiber modifies the wavefront of a laser beam to undo the scrambling of the initial beams by the fiber and this enables the transport of either illumination patterns or images through the fiber [1]. In the most common implementation, the SLM allows for the generation and the scanning of a single high-intensity focus at the distal end of the fiber with no additional optical elements, analogous to a confocal scanning microscope. This allows for the acquisition of images at a rate only limited by the update rate of the SLM (ranging from a few Hz to ~ kHz). This is relatively slow compared to a confocal microscope where pixel dwell times in the μs regime are routinely obtained. Hence, it remains a significant challenge to speedup the image acquisition rates with lensless endoscopes.

In this contribution, we show that a combination of speciality optical fibers and computation imaging techniques could address this gap in high-speed fluorescence imaging through optical fibers. We will describe the design and fabrication of a bending-resilient multi-core fiber bundle with a sparse arrangement of cores and capable of diffraction limited imaging with no pixelation artifacts. The sparse core layout allows for extremely low-cross talk ($< 20\text{dB}$) which leads to a fully diagonal transfer matrix [2], and the helical twisting of the fiber renders it insensitive to even strong mechanical perturbations [3]. These features allows the incorporation of a slow SLM for an initial static phase compensation and a fast galvo-scanner which performs the scanning operations, thereby matching the speed of state of the art microscopy systems [1].

In addition to the fiber itself, we leverage the sparsity of the signals commonly found in fluorescence imaging to use the toolbox of compressive sensing to speed-up the image acquisition. Here, a number of known illumination patterns (speckle) are projected on the sample and a single pixel detector is used to detect the fluorescence signal. In this case, the sparsity of the sample can be used to acquire fully resolved images where the number of projected patterns can be lower than the number of image pixels. The imaging performance of lensless endoscopes with translated speckle patterns generated by conventional scanners (in lieu of entirely random patterns) is examined both in numerical and physical experiments [4]. Further on, we also address the issue of calibrating the sensing matrix - a time and a memory intensive process. We show that a single interferometric characterization of the complex transmission matrix of the fiber can be used to both model and generate the desired illumination patterns to function as the sensing matrix. Such an *in-situ* interferometric calibration typically scales with the number of fiber cores ($\sim 10^2$) and avoids a tedious calibration of each illumination patterns (number of image pixels $\sim 5 \cdot 10^3$ patterns). These developments show that i) conventional scanners can be used to generate the speckle patterns and ii) an initial interferometric calibration can be used to generate the sensing matrix *on the fly* and account for system imperfections. Hence several demanding requirements on active optical components can be shifted to a speciality but passive optical fiber and adapted numerical techniques. These advancements opens a route towards more widespread adoption of lensless-endoscopy techniques by the end-users.

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