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Sensorless adaptive optics for multimode optical fibre endo-microscopy

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Abstract: We demonstrate focus optimisation through multimode optical fibre using sensorless adaptive optics. The optimisation can correct for the three-dimensional shift occurring when re-positioning the fibre into the system for chronic brain imaging.

1. Introduction

Diffraction-limited one-photon fluorescence microscopy of deep brain regions *in vivo* has recently been demonstrated through multimode optical fibres (MMF) [1,2]. An essential component of such endo-microscopy systems is a spatial light modulator. Wavefront shaping is indeed necessary to compensate for the random phase delays and mode coupling occurring inside the MMF. In particular, a focus can be formed at the MMF distal end using a suitable wavefront, which we determined using the transmission matrix method [3].

In such system, the transmission matrix characterises the light propagation between the wavefront shaping device and the distal imaging plane. Any change in the relative position between the wavefront shaping device and the fibre will lead to a substantial decrease in the quality of the focus and in the signal-to-background ratio. This is true even if the fibre remains in the same thermomechanical state, i.e. remains straight. However, the ability to perform chronic imaging is essential in many neuroscience experiments. We therefore seek to evaluate if sensorless adaptive optics can be used to correct the lateral and axial shifts in the MMF position [4,5]. We expect that this correction will have a spatially-invariant effect on the distal focusing performance and thus enable chronic imaging with minimal background fluorescence.

2. Methods

Light from a 488 nm continuous wave laser (CrystaLaser, DL488-020-S) illuminated a liquid-crystal spatial light modulator (SLM, Meadowlark Optics, HSPDM512). After being filtered through an iris, the first-order diffraction beam was coupled into a MMF (Thorlabs, FG050UGA, core diameter 50 µm, NA 0.22; L1: 100 mm; L2: 50 mm; and L3: 8mm - focal lengths). The distal end of the MMF was imaged onto a CCD camera (Basler pilot, piA640-210gm) by an objective lens (L4, Olympus, Plan N 20×, NA 0.4) and a lens (L5: 150 mm, focal length). The transmission matrix was evaluated at 50 µm from the distal MMF facet. A detailed description of the micro-endoscopy system (Fig. 1) is available elsewhere [1,5].

To evaluate the ability of sensorless adaptive optics to correct for the three-dimensional lateral shift, we removed the MMF from the system and re-inserted it. Different amounts of tip, tilt and defocus were then sequentially superimposed onto the pattern displayed by the SLM to form the focus at a given distal location (L1) while the intensity at that location was measured with the CCD camera.

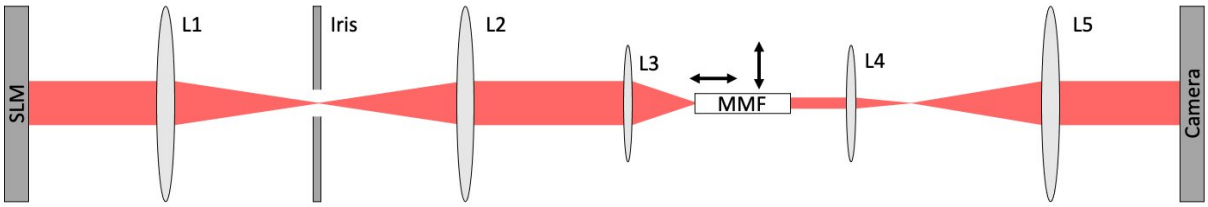

Fig. 1. Schematic of the experimental system.

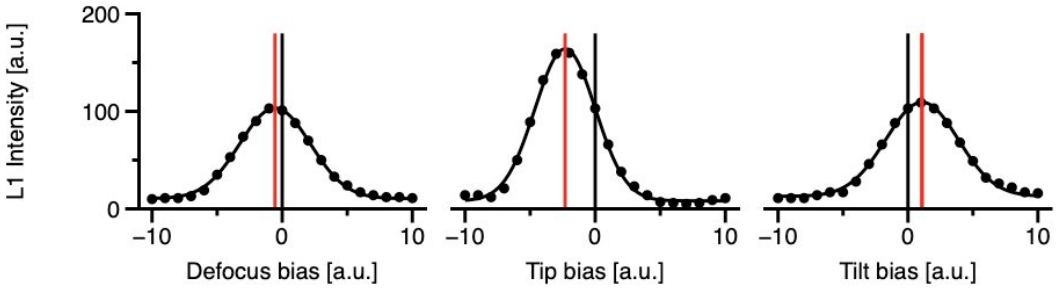

Fig. 2. Variation of the peak intensity at one distal location (L1) as a function of the amount of superimposed defocus, tip, and tilt bias applied. 21 bias values were tested with increments of $2\pi \times 0.0001\times$ increment number [rad].

3. Results

The variation in signal intensity at L1 as a function of the amount of defocus, tip, and tilt applied is shown in Fig. 2. Other quality metrics were previously tested and it was observed that minimising the background or analysing the background auto-correlation would be suitable alternatives for the experimental system described here. The signal intensity was selected because we anticipate that it will more straightforwardly be translatable to fluorescence-based sensorless optimisation.

A Gaussian fit was found to adequately describe the intensity variation for all three modes and was therefore used to find the optimal amplitude of each mode to superimpose onto the wavefront dictated by the transmission matrix to improve focusing after re-inserting. Even with the most careful manual re-positioning, the bias was rarely measured to be zero. Critically, the manual re-positioning had to be sufficiently close to the origin position such that a focus, even if weak, was detectable search domain of the adaptive optics algorithm.

4. Conclusion

Our results demonstrate that the three-dimensional shift due to fibre re-insertion can be evaluated and potentially corrected using sensorless adaptive optics. Correction of such system aberrations is essential to minimise the amount of background fluorescence which is the limiting factor in MMF-based endo-microscopy in live brain imaging applications.

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