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Rapid identification of coherent pupil functions from multiple intensity measurements

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ABSTRACT

By taking multiple input-output measurements, it is shown how to determine the input to an optical system that corrects unknown phase aberrations without interferometric measurements or online iterative optimization within a couple of seconds. It is shown to work in simulations and experiment. This technique may also be used to acquire the complex field in the pupil, hereby permitting a complex field image to be acquired.

Keywords: Coherence, aberrations, wavefront sensing, adaptive optics, imaging

1. INTRODUCTION

The identification of the optical propagation properties of unknown complex media has become in recent years of increasing research activity. In this short summary, a methodology for the rapid calculation of the coherent pupil function that optimizes propagation through an unknown optical media is presented. It differs in regard to many of the works currently in the literature as it relies on a computational and model-based approach to the identification of such a pupil function. Other methods approach its identification from a model-free optimization approach,[1] which whilst limited by its measurement based feedback can be made fairly robust and through choice of spatial light modulator and have even become sufficiently fast for practical purposes. Additionally, methods have been developed that approach this problem interferometrically[2] in order to improve the speed and performance of controlling light through these media. Nevertheless, there is space for additional methodologies such as the following, where the former methods may not be applied.

As an outline, it is briefly described how from a set of input-output data, it is possible to quickly identify the pupil function that optimizes focusing. It is done by forming and then solving a highly constrained phase retrieval problem by minimizing the difference between the measured and modeled speckle patterns. The algorithm that is employed is a modification of the author's previous work to work with coherent imaging, it is called TIP.[3] It is demonstrated in experiment that within a couple of seconds it is possible to make a significant improvement to the PSF.

2. THE IMAGING INPUT-OUTPUT MODEL

As is common in these approaches the system is modeled as being a linear operation and the relationship between the input field x and output field y from the medium is given by:

$$y = \mathcal{H}x \tag{1}$$

where $y \in \mathbb{C}^{M_o N_o}$, $x \in \mathbb{C}^{M_i N_i}$ and $\mathcal{H} \in \mathbb{C}^{M_i N_i \times M_o N_o}$ and $M_i \times N_i$ is the size of the pixel grid for control with $M_o \times N_o$ for detection, this is commonly known as the *transmission matrix*. In this case, it is necessary to identify the $M_i N_i M_o N_o$ components of H to correctly model the system; a number that can quickly run into the

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millions for modest grid sizes. To overcome this scaling problem, the next step is to assume that it is possible to model the system as a convolution in the following way:

$$y = h * x \tag{2}$$

here, all that has occurred is a change of notation and thereby supplying a constraint on the form of H. In the Fourier domain, this well-known relationship can then be modeled as:

$$Y = H \cdot X \tag{3}$$

where now $Y \in \mathbb{C}^{N\times N}$, $X \in \mathbb{C}^{N\times N}$ and $H \in \mathbb{C}^{N\times N}$ with the grid sizes being square with side length N. Now, there are a reduced number of elements that one needs to find to identify the medium. These are the N^2 elements of the H spectrum, rather than N^4 elements of $\mathcal{H}$.

The simplification one has made here is that one is only treating the isoplanatic case. Each position in the input field is affected by propagation in the same way and is the imposition of a particular structure on the matrix H. This approach still has certain validity for aberrations outside of this plane as is commonly practised, so long as one only cares about correction on axis.

To solve this problem, one begins by making a series of input and output measurements. This generates a set of $\{Y_k\}$ and $\{X_k\}$ and since it is impossible to measure the complex field using a camera there is ambiguity in the value of the Y_k's, therefore, one must solve the following optimization problem:

$$\min_{H, Y_k} ||Y_k - H \cdot X_k||_2 \tag{4}$$

The value for H if $\{Y_k\}$ was known without ambiguity would be the least-squares solution given by:

$$H = \frac{\sum_{k=1}^{K} X_k^* \cdot Y_k}{\sum_{k=1}^{K} |X_k|^2} \tag{5}$$

Since, this is not known it must be estimated. To do this, the results of this solution are then projected back using the input data giving an new estimate for the value of $\{Y_k\}$. For each input-output pair the calculation is made:

$$Y_k = H \cdot X_k \tag{6}$$

The final step is to ensure the continuing fidelity to the data, thus the Fourier transform of the spectra must have intensity equal to that of the input images i_k, that is:

$$Y_k = \mathcal{F}^{-1}\left\{i_k \exp(j\angle\mathcal{F}\{Y_k\})\right\} \tag{7}$$

With the initial $\{Y_k\} = \mathcal{F}^{-1}\{i_k \exp(j\mathbf{rand}[-\pi, \pi])\}$, the iterative procedure can be described as:

1. Estimate H by least-squares (Eq. 5).
2. Estimate each Y_n by projection (Eq. 6).
3. Constrain Y_n using known intensity distributions (Eq. 7).

A diagram of the model used here is shown in Fig.1, it shows that the known input field x passes through a medium that may be modelled as a $4f$ system with an unknown phase function in the pupil. This produces an output field y of which the intensity can be measured.

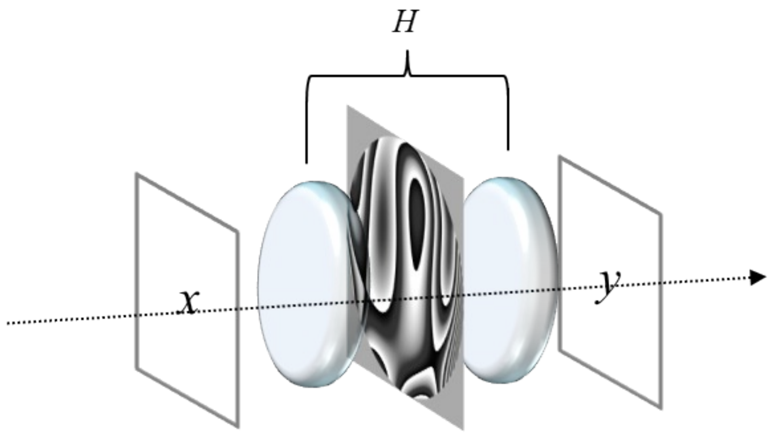


Figure 1: The isoplanatic model optical system that is treated here. A known input field x passes through an unknown medium that is assumed to produce a coherent convolution of the field producing output field y

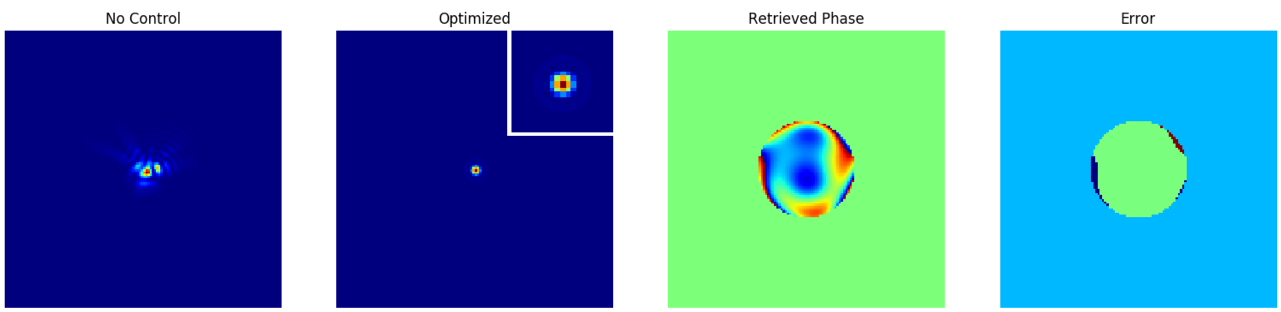


Figure 2: Simulated data showing the retrieval of an unknown phase distribution through observation of multiple intensity images. Left to right: the intensity out with no control; the intensity out after retrieval and correction; the retrieved phase; and the residual error in the retrieved phase. The final phase is known up to a piston shift and phase wrapping.

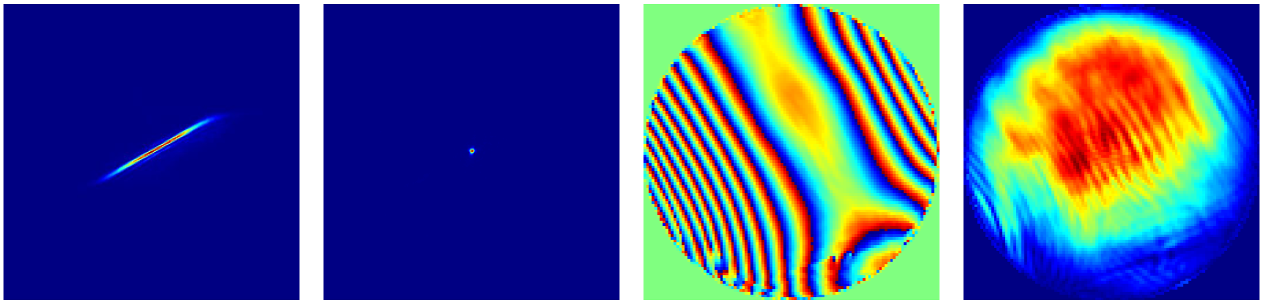
3. METHOD VERIFICATION

To test the methodology a simulation is run with the components as in Fig.1, by generating an unknown phase screen based on Zernike coefficients up to Noll index 20 to give an measured intensity output $|y|^2$. The inputs for generating the dataset are known to be phase-only patterns consisting a known random distribution of Zernike modes, i.e. using the same basis as the unknown phase error (this is not necessary).

The images (K=16, N=128) are run through the algorithm for 20 iterations to ensure convergence taking around 5s. The phase pattern to apply to the virtual SLM is found by taking $\varphi = -\angle H$. The results for this simulation are shown in Fig.2 and clearly show that the algorithm is able to retrieve the unknown phase, thereby, correcting the aberrated PSF to a spot. It is estimable up to an unknown piston phase, as with all phase retrieval techniques, and the 2π steps due to phase wrapping can be seen in the residual error plot in Fig. 2.

To experimentally verify the method, a 488nm laser source (100mw Sapphire, Coherent, U.S.) is used to illuminate a spatial light modulator (512x512, Meadowlark Optics, U.S.) and thereafter focused onto a camera (USB 3 uEye CP Rev. 2, IDS, Germany) with a $6f$ system of achromatic lenses (AC508-200-A-ML, Thorlabs, U.S.). An astigmatic ophthalmic lens is placed in the central pupil of the $6f$ system. This is in a plane conjugated with the SLM.

A set of 16 known input phases with Zernike modes are applied and the intensity on the camera is registered. The algorithm is run on this set of input-output data and the unknown phase is recovered using 52x52 phase points and 20 iterations taking again around 5 seconds. The conjugate phase of the retrieved H is applied as



(a) (b) (c) (d)

Figure 3: (a) The pre-retrieval output intensity. (b) The post-retrieval and correction output intensity. (c) The retrieved phase in the pupil, which is used to correct (a). (d) The retrieved amplitude of the field in the pupil.

an input and the resultant PSF is measured. The results of this are shown in Fig. 3, where one can observe the improvement to the PSF made by the estimated phase.

4. COMPLEX PUPIL IMAGING

As an extension to this method, as the technique is able to identify the isoplanatic coherent pupil function, it is suited to the purpose of also imaging in the pupil. To demonstrate this in theory a set of input-output measurements are taken assuming that there is a phase object in the pupil, in this case it is a confocal image of a cell converted into a phase object. This was chosen to mimic the morphology of biological samples, which is a potential end application. The light that passes through this simulated cell is then focused and the speckle patterns produced with different input fields are processed using the projective algorithm.

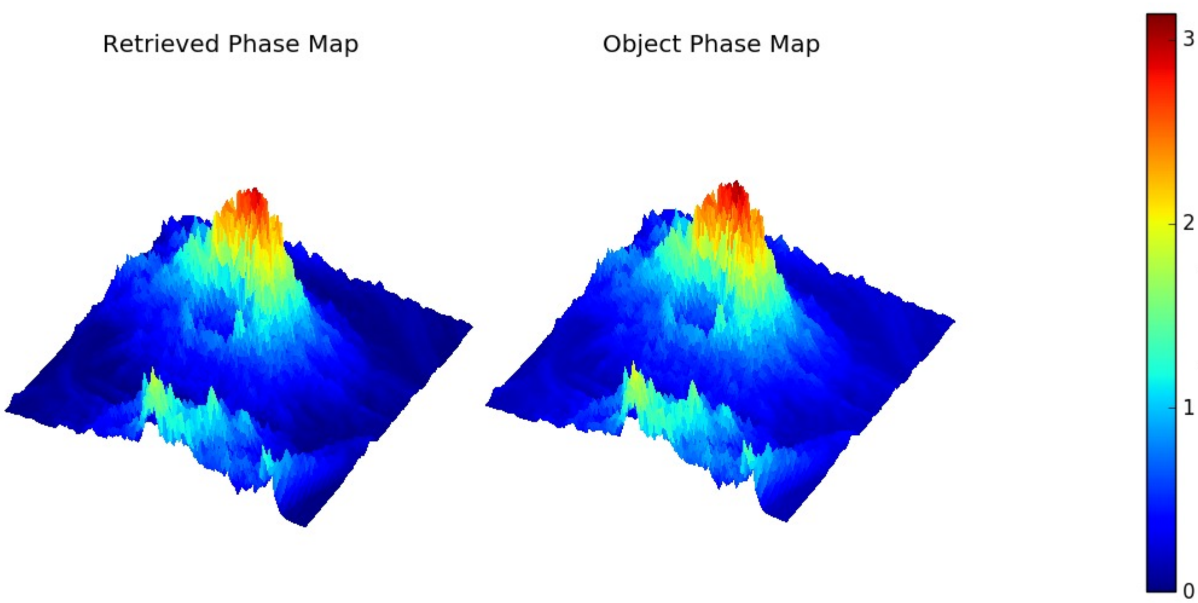


Figure 4: A surface plot showing the comparison between a simulated phase distribution of a cell and the reconstruction after $K = 8$ measurements of input-output data transmitted through the cell. The reconstruction requires at least 10 iterations of the algorithm for maximum reconstruction accuracy.

These results are show in Fig. 4 and just as in the previous case, it is possible to obtain both the phase and intensity distribution in the pupil. Here the object was phase only and so this has been reproduced, one can observe the reconstruction in this simulated case from $K = 8$ images gives an almost perfect reconstruction after 10 iterations in around 3 seconds.

After the success in the simulations, the same was done in the experiment. The cell phase pattern is applied to the SLM and the PSF is recorded with several diversity measurements. From this information the algorithm is run and it is attempted to retrieve the phase pattern of the cell that has been applied to the SLM. The results of this experimental test are shown in Fig. 5. It can be observed that the reconstruction of the cell recovered only contains the low order spatial frequency information, but is not able to detect the high order variation in the applied pattern.

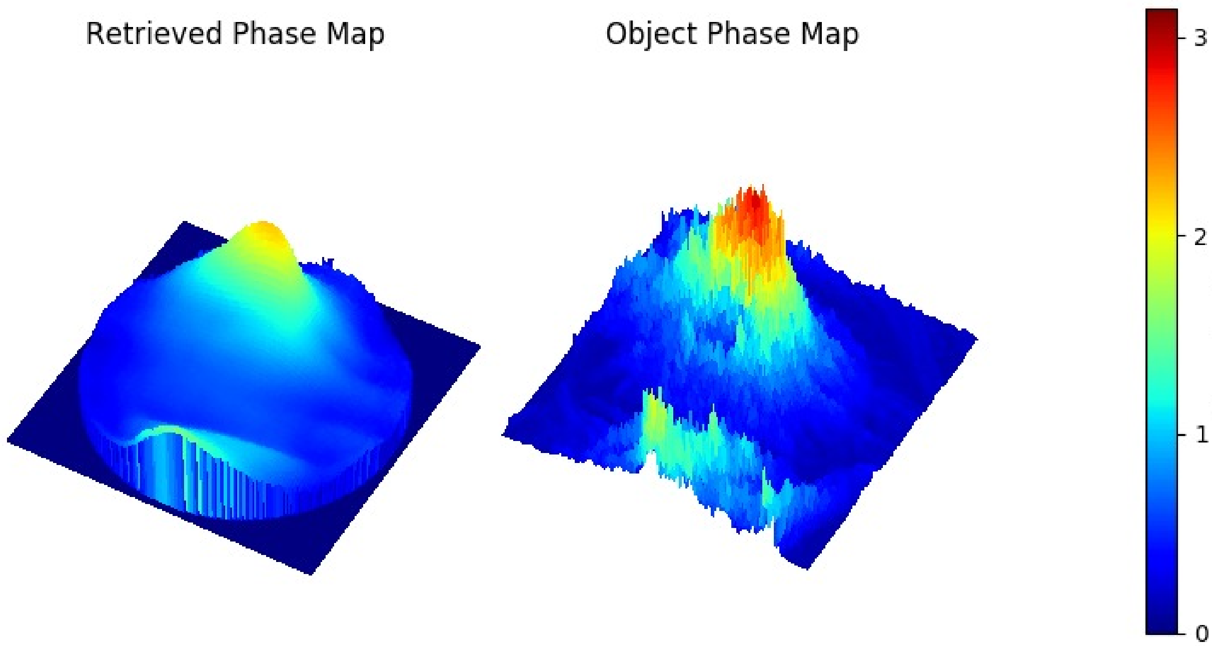


Figure 5: A surface plot showing the comparison between the phase distribution of a cell applied to the SLM and the reconstruction after $K = 16$ measurements of input-output data "transmitted" through the cell.

The reasons for this is that the current setup does not have the sufficient dynamic range to successfully record this information. Information in the speckle pattern far from the centre of the distribution is required for the high frequency information and therefore is lost in the noise with a fixed exposure. This fact has been confirmed by simulations that limit the spatial extend of the speckle pattern and cause this resultant loss in high spatial frequency information.

5. CONCLUSIONS

To conclude, it has been demonstrated how from a small set of input-output measurements it is possible in theory and experiment to identify the pupil function that corrects for the effects of an unknown phase aberration using the model and algorithm presented. This approach may be useful in situations where interferometric identification is impossible and online sequential optimization is too slow and costly. The major drawback to this current technique is that it acquires a correction that by its design is inherently isoplanatic meaning that this technique may not be used for highly anisoplanatic systems such as optical fibers. Improvements to make this anisoplanatic can be made, at the cost of control accuracy (i.e. by limiting the number of available modes), but has not been the focus of this paper.

The technique has been shown as a method that may be used to do imaging of the complex field, retrieving both the phase and amplitude distribution in the pupil plane of the model system. The experimental results show the first step towards the implementation of this with a low order reconstruction resulting from the limited dynamic range of the camera. It is believed that with changes to acquisition method and the optical system used it will be possible to record the optical field with increasing resolution and thus make this technique applicable to the quantitative phase imaging of biological samples.

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