Deep learning estimation of eye aberrations from simulated double-pass retinal images

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Image-based wavefront sensing allows determining optical aberrations directly via the Point Spread Function (PSF) without specialized sensors. In contrast to astronomical measurements, ocular measurements are conducted using a double-pass method. We develop a deep learning model to estimate 12 Zernike terms in the wave aberrations (excluding piston and tilt) matching each PSF. After training, the model achieves low Root Mean Square Error for the Zernike coefficients with fast one-shot inference of 3ms. These results from simulations serve as base for future work generalized to experimental data.

Keywords: deep learning; ocular aberrations; Zernike polynomials

INTRODUCTION/PURPOSE

Image-based wavefront sensing estimates the wavefront from acquired images without needing specialized wavefront sensors. Current methods suffer from slow iterations and low accuracy with recent works using deep learning models to address these limitations. Common applications involve Adaptive Optics (AO) systems [1] or enhancing acquired images in post-processing [2], primarily in astronomy. The current study investigates the estimation of eye aberrations in a sensorless way. We simulate ocular double-pass PSFs and train a deep learning network to calculate the Zernike coefficients for the associated aberrations.

METHODS

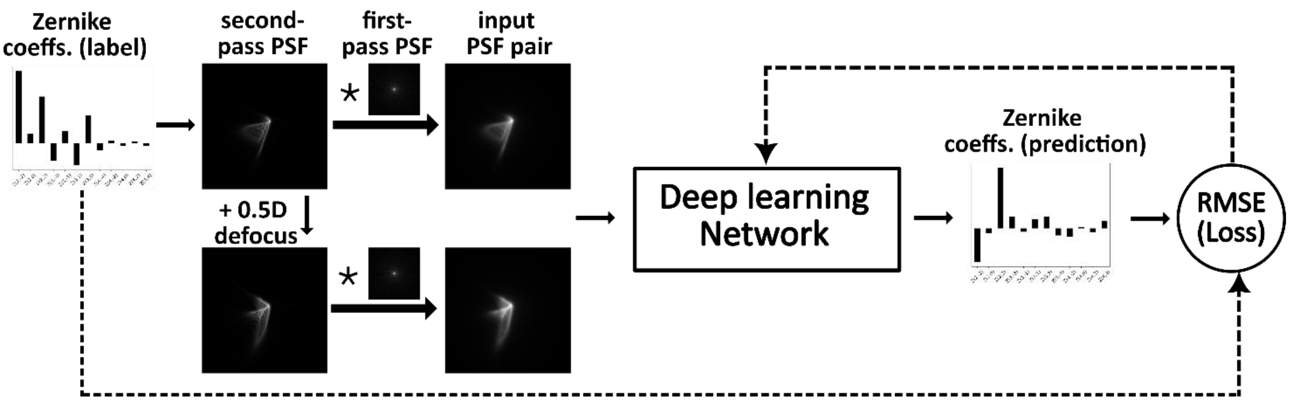

Figure 1 Schematic of the training setup for the deep learning model

Each simulated PSF is computed based on randomly generated Zernike coefficients using the Fraunhoffer approximation theory on a 5mm pupil. This aberrated PSF is then correlated with a diffraction-limited PSF, representing the first pass through the system for a small 2mm aperture [3]. We use the 12 Zernike terms excluding piston and tilt, and sample them from a uniform distribution with coefficients ranges encountered in healthy eyes [4]. For the simulations, the wavelength is set at 555nm. We preprocess the PSF images by taking the square root of their intensities, and resizing them to 128x128 pixels corresponding to approximately 1.08deg. To avoid sign ambiguity in the even Zernike terms, each simulated PSF is paired with a slightly defocused version of itself by adding 0.5D defocus. In total, approximately 80000 PSFs are used for the training and 8000 PSFs for the validation. Figure 1 shows the training setup. The deep learning network receives pairs of PSFs as input and it predicts the corresponding Zernike coefficients. The loss of the training is the Root Mean Square Error (RMSE) between the sampled coefficients (labels) and the predicted coefficients. The deep learning architecture is a custom smaller variation (33000 parameters) of the Densenet model [5].

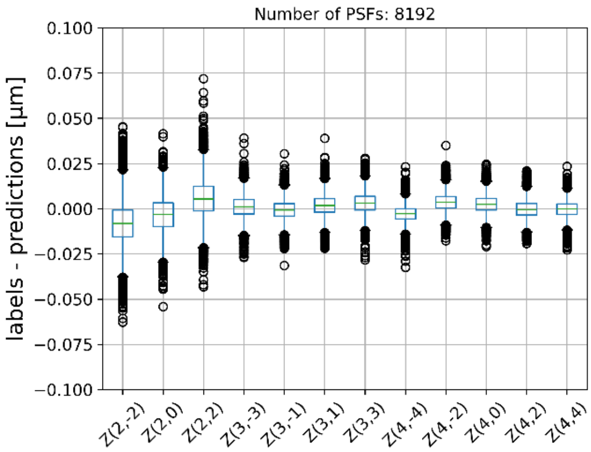

Figure 2. Boxplot of differences between the Zernike labels and the model predictions

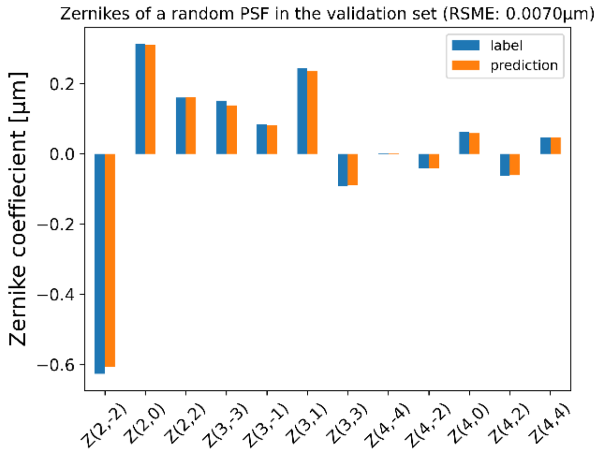

Figure 3. Zernike label compared to prediction for a random PSF in the validation set

RESULTS

Figure 2 shows the distribution of differences between the label and predicted values of various Zernike coefficients, measured in µm. The model achieves a mean RMSE of 0.008µm, or 2.5% when compared to the mean absolute Zernike coefficient. Figure 3 showcases the performance of the model on a PSF close to the mean RMSE. Moreover, the prediction happens in one-shot with inference time of 3ms on a consumer GPU (NVIDIA GeForce RTX 4070).

CONCLUSIONS

We demonstrated that deep learning can accurately estimate eye aberrations using simulated double-pass PSF images based on healthy eye data. Future work involves applying our method to experimental PSF data. Our method could potentially transform commercially available PSF-capturing instruments into aberrometers without the need for additional hardware.

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