Image-Based Active Wavefront Control Using a Neural Network-Driven Deformable Mirror

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Optical atomic clocks based on single trapped ions are among the most precise instruments ever built, with systematic uncertainties now reaching beyond the 10^{-18} level. One important source of systematic error arises from imperfections in the wavefront of the interrogation laser: deviations from the ideal beam profile introduce uncontrolled light shifts, which lead to frequency perturbations. Correcting these wavefront aberrations therefore directly reduces a key contribution to the systematic uncertainty budget.

We develop an image-based controller that actively compensates low-order wavefront aberrations using a commercial deformable mirror. A convolutional neural network (CNN), trained on images of a CCD camera, infers the relevant Zernike coefficients from a single camera frame and maps them directly to mirror correction commands – without requiring a dedicated wavefront sensor. This single-frame approach avoids multi-step phase retrieval and keeps the beam available for experiments the vast majority of the time.

We present the training procedure, validation, and a proof-of-concept demonstration of the CNN-based controller. As the approach requires only a camera image of the beam and is independent of the specific beam shape or application, it is broadly applicable without requiring complex alignment or additional dedicated sensors.

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