Control system design and implementation for compensating the eye's wave aberrations

Kaccie Y. Li[1]

[1]Abbott Medical Optics, Groningen (the Netherlands)

Kaccie.li@amo.abbott.com

Purpose

To provide a rigorous treatment of the classical adaptive optics (AO) control loop. I show how the AO control problem can be posed in a framework analogous to linear quadratic methods used in optimal control. Examples will be taken from the latest software upgrades made on a MEMS-based AO retinal imager.

Methods

The classic AO system setup, which consists of a Hartmann-Shack type wavefront sensor and a deformable mirror (DM) operating in closed loop, is revisited from a control systems perspective. The control problem is formulated in the discrete-time domain as shown by the block diagram in Fig. 1. Linear quadratic methods are then applied to obtain the general form of a class of algorithms sometimes referred to as minimum-variance reconstruction. To make the system linear, influence functions for the DM were measured with a custom-built phase shifting interferometer (Fig. 2) and inverted to linearize the otherwise nonlinear static response of the MEMS DM. System stability and retinal image quality served as guidelines for determining the actual design parameters. This was made possible by developing a separate software package for an AO scanning laser ophthalmoscope (Roorda Lab, UC Berkeley) purposely written for prototyping new control algorithms. Eyes with various levels of refractive error, but are otherwise healthy, were imaged over a 6-mm pupil using 840-nm light. Residual wavefront error and most importantly, the resultant images of the cone photoreceptor mosaics are used to evaluate the quality of the wavefront correction.

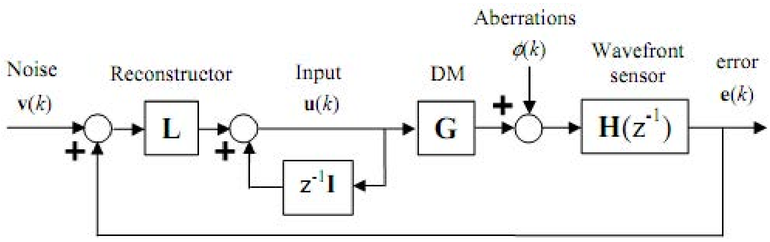

Fig. 1. Block diagram adopted to set up the control problems

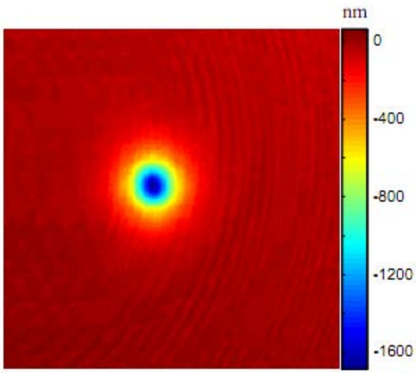

Fig. 2. Influence function of the DM measured by phase-shifting interferometry (λ = 635 nm)

Results

The classical AO control loop, standard in many current vision AO systems, has been expressed in a form where linear quadratic methods can be applied. Through this approach, it becomes evident that “direct-slope control” is the simplest case where no prior information on aberrations and noise is incorporate into the design. Incorporating aberration and noise statistics into the controller design has lead to improvements in retinal image quality and a relative increase in image brightness (≈ 10 percent) due to confocal image formation. For the very first time, the smallest cone photoreceptors at the foveal center have been resolved using an AOSLO (Fig. 3), but we are only able to do so in about 20 percent of our subjects. Residual wavefront error estimated from wavefront sensor data was not a good indicator of the actual retinal image quality.

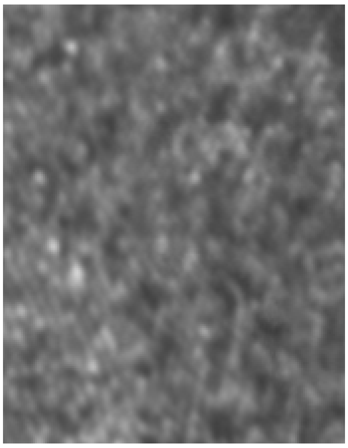
Fig. 3. AOSLO image of cone photoreceptors at the very center of the fovea

Conclusions

Linear quadratic methods add another dimension to wavefront control where noise and aberration statistics among other features can be explicitly incorporated into the control algorithm design. The result is a better AO system in terms of robustness and performance.