

Hybrid adaptive-optics visual simulator

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We have developed a hybrid adaptive-optics visual simulator (HAOVS), combining two different phase-manipulation technologies: an optically addressed liquid-crystal phase modulator, relatively slow but capable of producing abrupt or discontinuous phase profiles; and a membrane deformable mirror, restricted to smooth profiles but with a temporal response allowing compensation of the eye's aberration fluctuations. As proof of concept, a phase element structured as discontinuous radial sectors was objectively tested as a function of defocus, and a correction loop was closed in a real eye. To further illustrate the capabilities of the device for visual simulation, we recorded extended images of different stimuli through the system by means of an external camera replacing the subject's eye. The HAOVS is specially intended as a tool for developing new ophthalmic optics elements, where it opens the possibility to explore designs with irregularities and/or discontinuities. © 2010 Optical Society of America

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Visual simulation is an application of adaptive optics specifically developed to study the impact of aberrations on vision. A visual simulator is basically an adaptive-optics system coupled to a stimulus generator. Adaptive optics in this case is not necessarily used to correct the ocular and system aberrations [1,2] but to produce a controlled aberration pattern through which the subject is presented with different stimuli in order to study the effect on visual performance. Visual simulation has been successfully used both to study high-level features of the visual system [3,4] and as a tool for developing ophthalmic-optics elements [5,6]. Another application would be the use as an advanced phoropter. The initial implementations of the concept made use of a low-cost deformable mirror [3,5]. Since then, several improvements or modifications have been presented, including either a high-quality membrane deformable mirror (MDM) [4,7] or a liquid-crystal programmable phase modulator (PPM) [6,8]. Each technology presents advantages and drawbacks. The mirror is a fast device that can dynamically correct the ocular aberrations in real time but, being a continuous surface, can produce only a limited range of smooth phase shapes. On the contrary, the PPM has virtually no continuity constraints and therefore can be used to produce a wider range of more irregular aberration profiles, even with discontinuities. However, its slow response makes it unfit to follow the eye's rapid fluctuations.

In this Letter, we present a hybrid adaptive-optics visual simulator (HAOVS) that includes two phase-manipulating devices, one MDM and one PPM, working in tandem to produce a system combining the advantages of both technologies. This can be regarded as a version of the woofer–tweeter combination recently proposed [9,10].

A schematic view of the HAOVS is presented in Fig. 1. The design is similar to previous versions of visual simulator [5–7], with the important difference of having two active elements conjugate to the eye's pupil. The MDM is a 97-actuator high-quality mirror (Xinetics Inc., Devens, Mass., USA). The PPM

(Hamamatsu X8267, Hamamatsu Photonics K. K., Japan) has 768×768 pixel resolution and is especially suitable to induce static phase patterns with elaborate profiles. A 780 nm diode laser illuminating the eye through a beam splitter (BS) can be used to measure ocular aberrations with a Hartmann–Shack (H–S) sensor [11] and correct them with the MDM in a closed loop. A green He–Ne laser (543 nm), not entering the eye, can also be used to operate the MDM in a closed loop and to experimentally record the point-spread function (PSF) associated with the combined phase profile introduced by the MDM-PPM tandem in order to objectively test its impact on image quality. A cold mirror (CM) reflects most of the green light toward the CCD camera for PSF recording while transmitting virtually all the IR light for wavefront sensing. Finally, the CCD camera can be removed and the subject can be presented through the modified optics with a range of visual stimuli produced in a monochrome (green) microdisplay (LE-700, Liteye Systems Inc., Centennial, Colo., USA) in order to study the subjective impact on vision of the

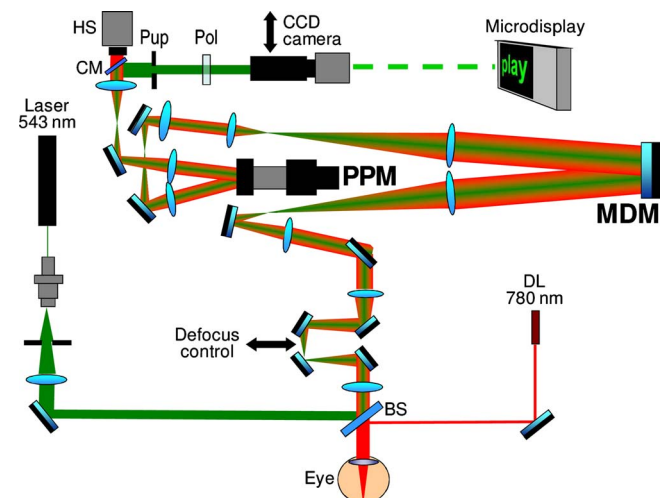


Fig. 1. (Color online) Schematic view of the HAOVS. See text for details on components.

phase profile.

Phase generation with the PPM is wavelength dependent, and therefore both objective and subjective testing in the HAOVS is restricted to monochromatic light. Another requirement of the PPM is the use of polarized light, achieved by means of polarizer Pol. This polarizer is not in the path of light reaching the H-S sensor, thus preventing the corresponding intensity loss and improving the MDM closed-loop performance. On the contrary, the polarizer is in the path of light reaching the CCD camera and coming from the monitor, ensuring correct phase manipulation for both PSF recording and visual testing. This has no impact on the ocular wavefront [12,13] and does not affect MDM functioning. Additionally, apart from Haidinger's brush and other faint entoptic phenomena, the human eye is virtually blind to polarization [14], and the use of polarized light is not expected to affect visual simulation outcomes.

A customized software package has been developed to control the apparatus. Once calibrated as described elsewhere [15], the PPM does not require closed-loop operation owing to its high fidelity. On the contrary, the MDM is always operated in closed loop in combination with the H-S sensor. The software also controls a motorized Badal optometer to modify defocus and/or change stimulus vergence. A separate stimuli generation software package based on commercially available libraries (Cambridge Research Systems, UK) can be used for a wide range of visual testing.

To illustrate the capabilities of the HAOVS to generate and evaluate complex phase profiles, we present in this Letter results for the phase map in Fig. 2(a), selected as an example of an abrupt profile impossible to produce with a deformable mirror alone owing to its phase discontinuities. In essence, it is a trifocal element where the pupil is divided into six equal radial sectors with three pure defocus values (0, 1, and 2 D). To demonstrate the feasibility of MDM closed-loop operation through a discontinuous phase map, we corrected the ocular aberrations of a real subject through the trifocal profile in 780 nm. The reference positions of the H-S spots were obtained from an image recorded with the profile on the PPM and the system aberrations corrected by the MDM. The aberration rms can be seen in Fig. 2(b). It is reduced to values around $0.15 \mu\text{m}$, somewhat higher than those typically obtained in closed-loop correction owing to the inhomogeneous shape of some

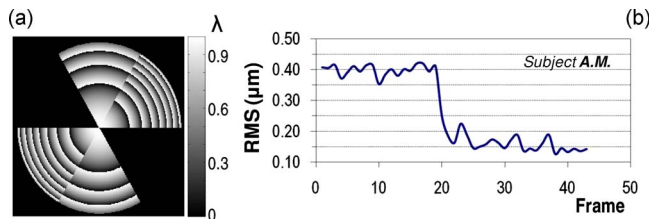


Fig. 2. (Color online) (a) Wrapped phase map in 780 nm of the trifocal phase profile consisting of six discontinuous radial sectors. (b) Evolution of high-order rms for a real subject. The MDM correction close loop started around frame 18.

spots caused by the discontinuous phase map. However, this result shows the potential of the system for simultaneous aberration correction and visual testing through exotic phase profiles. A different approach would be to stop the MDM closed loop after correcting the subject's aberrations with the PPM off and then adding the desired phase pattern. This would mean correction of the static component of the ocular aberrations only, but the closed loop routinely yields rms values below $0.1 \mu\text{m}$ when no phase profile is present on the PPM.

As an example of objective testing with the HAOVS, the Strehl ratio as a function of defocus was obtained from experimentally recorded PSFs for the trifocal profile in green light, Fig. 3(a), with the MDM correcting the residual system aberrations excluding defocus ($0.05 \mu\text{m}$ of final rms over a 4.8 mm pupil). Defocus was scanned by means of the motorized Badal optometer in 0.1 D steps, with a finer 0.05 D scan around the three nominal defocus values (0 D, 1 D, and 2 D). Figure 3(b) shows three experimentally obtained PSFs producing peak Strehl ratio values. Figure 3(c) shows the experimental Strehl ratio values together with the theoretically computed values for the combination of trifocal profile and system residual aberrations after correction. As a further example, the Strehl ratio analysis was repeated using the MDM to add the aberrations from a real eye ($0.27 \mu\text{m}$ of high-order rms for a 4.8 mm pupil). Figure 4(a) shows the combination of the subject's ocular aberrations and the trifocal profile. Examples of experimental PSF images are presented in Fig. 4(b). The experimental and theoretical Strehl values in Fig. 4(c) show that the subject's aberrations degrade the trifocal properties of the phase profile, indicating that it is not a promising solution for increasing depth of focus. However, it is important to note the agreement between experimental and theoretical values, revealing the capability of the HAOVS as a tool to test discontinuous phase profiles in combination with smooth aberrations present in real eyes.

In a typical situation of advanced phase profile testing by visual simulation, the optical analysis

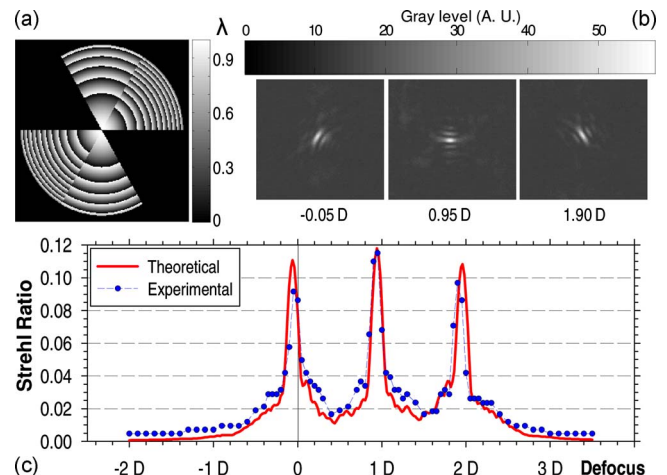


Fig. 3. (Color online) (a) Wrapped phase map of the trifocal phase profile for 543 nm. (b) Examples of experimental PSFs. (c) Strehl ratio as a function of defocus.

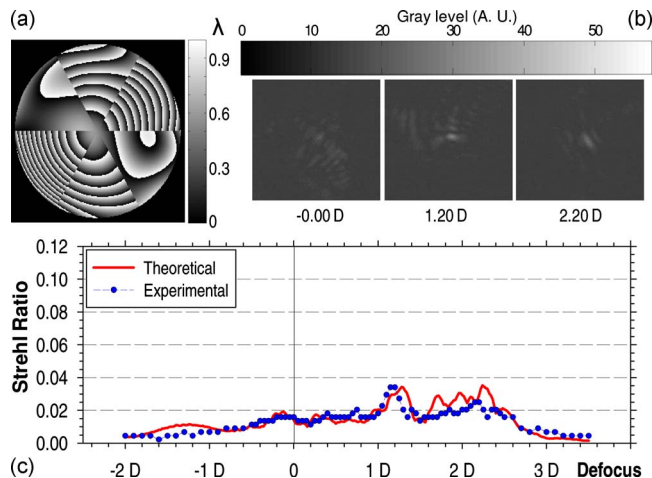


Fig. 4. (Color online) (a) Combination of trifocal profile and ocular aberrations from a real eye. (b) Examples of experimental PSFs. (c) Strehl ratio as a function of defocus.

would be followed by subjective testing. An alternative, more illustrative in this case, is to present extended images showing how a visual stimulus would be seen through the phase profile [16]. To this end, the subject's eye was replaced by a CCD camera with a 50 mm objective ($f/1.8$), acting as an electronic observer. Figure 5 shows a series of images for two different stimuli as a function of defocus with and without the trifocal profile. As expected, image quality with the profile is worse on-focus but better off-focus.

As a final comment, it can be mentioned that the recently developed technology for phase manipulation based on liquid-crystal-on-silicon devices [17] is regarded as a promising alternative to optically addressed PPMs, with faster temporal response. However, the optically addressed PPM could still present some advantages in terms of diffractive efficiency, which can produce undesired artifacts for large amounts of aberrations [18], and spatial resolution.

In summary, we have developed an HAOVS that synergistically combines two different technologies of wavefront manipulation: a liquid-crystal phase modulator, ideal for static production of phase profiles even with discontinuities; and a high-quality de-

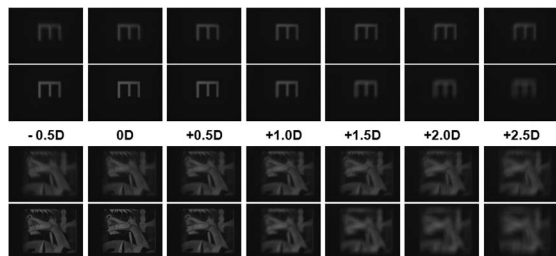


Fig. 5. Images through the HAOVS with and without the trifocal profile (respectively, top and bottom rows for each stimulus). Angular dimensions: E-letter, $2.25^\circ \times 1.68^\circ$; horse, $5.39^\circ \times 4.35^\circ$.

formable mirror for dynamical correction of ocular aberrations in closed loop. To illustrate the capabilities of the device, a phase profile composed of six discontinuous radial sectors has been tested. The feasibility of MDM closed-loop operation through a discontinuous phase profile has been demonstrated in a real subject. The throughfocus performance of the profile has been objectively tested both isolated and in combination with the aberrations from a real eye, with good agreement between experimental results and computational simulations. Additionally the potential of the device for visual simulation has been shown by recording images of different visual stimuli through the system with a camera replacing the eye. The HAOVS is a useful tool for designing new advanced ophthalmic optics elements, opening the possibility to explore discontinuous phase profiles and diffractive optics elements.

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