Reducing speckle in double-pass systems using focus tunable lenses

Carlos E. García-Guerra[1]*, Mikel Aldaba[1], Monserrat Arjona[1], and Jaume Pujol[1]
[1]Centre of Sensors, Instruments, and System Development (CD6),
Technical University of Catalonia (UPC), Terrassa, Spain
*Corresponding author: carlos.enrique.garcia@cd6.upc.edu

Speckle arises in double-pass systems when coherent light is reflected by the retina. Since it degrades the images that are used to characterize the eye, there is special attention in reducing speckle when working with instruments based on retinal reflection. We present in this work the results of reducing speckle in a double-pass system by varying the vergence of the beam entering the eye with an electro-optical liquid lens during the recording of images. Speckle reduction was verified in an artificial and a real eye following the implementation of the method.

Keywords: speckle; double-pass; optical quality; tunable lens

1. Introduction

The double-pass technique [1] has arisen as an excellent tool to obtain an overall estimation of the retinal image quality and is even used by commercial systems in clinical environments [2]. In this technique, the aerial image of a point source projected on the retina is used to estimate parameters that describe the optical performance of the eye, such as the point-spread function (PSF) and the modulation transfer function (MTF). Since relying on reflections of coherent light in the retina, a rough surface composed of photoreceptors that scatter light back with a random phase [3], double-pass images are affected by speckle, a noise which can alter the determination of parameters describing the quality of the eye under assessment [1]. Therefore, the speckle reduction plays and important role not only in double-pass instruments but also in all those systems based on retinal reflection, such as Hartmann-Shack aberrometers.

Different techniques to reduce speckle have been implemented along the history of double-pass systems. For instance, based on the fact that the eye presents speckle structures varying in time, temporal integration in the recording and averaging of short-exposure frames were the first methods used to deal with this noise [1]. Angular and wavelength diversity are other approaches that have been explored in visual optics to reduce speckle. The former has been implemented by deviating the rays reaching the retina with scanning mirrors [4] and rotating diffusers [5], while in the latter case a broadband laser is used to produce uncorrelated patterns [4, 6].

In this work, we reduced speckle in a double-pass system by varying the vergence of the beam entering the eye with an electro-optical liquid lens, a device with a tunable focal distance. The variations in the focal position change the path traveled by light [7] and shift longitudinally the position of the image plane with respect the retina. Such displacements are induced during the recording with magnitudes larger than the phase-space speckle size [7] to produce uncorrelated patters, but without compromising the determination of the eye's optical quality from the image by limiting the variations the optical power to ±0.15 diopters (D).

Although equivalent concepts have been used in other fields [8], to our knowledge, this method for reducing speckle has not been applied before in visual optics.

2. Methods

Experimental Setup

Figure 1 depicts the setup used to implement the speckle reduction. A point source coming from the collimated laser diode LD (λ=780nm) is imaged on the retina after passing through the circular diaphragm P1 of 2mm diameter and the spherical corrector composed by lenses LL and L1 [9]. After reflected by the retina, the light exist the eye and is translated to the exit pupil plane by lens L1. There, the light reaches the pupil P2 of 4mm diameter and then passes through LL and beam splitter BS before being focused on the CCD-DP camera in charge of recording double-pass images with a pixel resolution of 8.3×8.3um.

The focal distances of the commercial tunable device LL and the fixed lens LL are, respectively, f_{LL}=36 to 132mm and f_{L1}=50mm and they can be used to set up vergences in the beam entering the eye from +7.77 to -12.42 diopter (D). LL is biased with a remote-controlled power supply and the dichroic mirror DM is mounted on a vibrating motor, so that it can be used as scanning mirror to break coherence of light.

Measurements

We carried out measurements on an artificial (AE) and a real eye (RE) of a healthy subject under normal viewing conditions. Using an integration time of 240ms, we captured three images for each eye under the following combinations: P0/ON (reference, I0), P0/OFF (full speckle, IS), P0+p/OFF (reduced speckle, IR); where P0 is the optical power in the spherical corrector with which it was obtained the image with the best optical quality (narrowest spot), p is a 7Hz alternating defocus of 0.15D peak, and ON-OFF refers to the state of the scanning mirror. This frequency and amplitude allowed us, respectively, to produce variations within the integration time of the CCD camera and, based on simulations in Zemax, to have Strehl ratios (SR) higher than 0.8 during the recording (SR=0.94 for the average case). Regarding the SR, it was obtained as the ratio of the area under the MTF to the one of the diffracted limited case [10].

We computed the speckle contrast SC [6] radially considering the centre of mass of the image as the position from where all radii were computed. Moreover, we obtained the relative errors in the Modulation Transfer Function MTF and Strehl ratio SR as $e_M=|MTF_0-MTF_I|/MTF_0$ and $e_S=|SR_0-SR_I|/SR_0$, respectively.

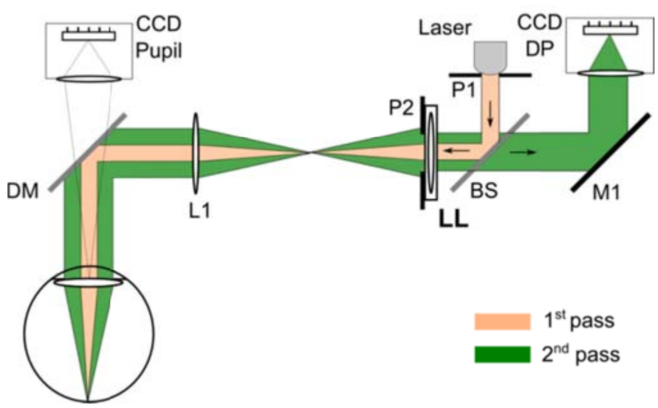

Figure 1. Schematic diagram of the setup used to perform the speckle reduction. Laser diode: LD, beam splitter: BS, tunable lens: LL, fixed lens: L1, pupils: P1 and P2, dichroic mirror: DM, cameras: CCD-Pupil and CCD-DP.

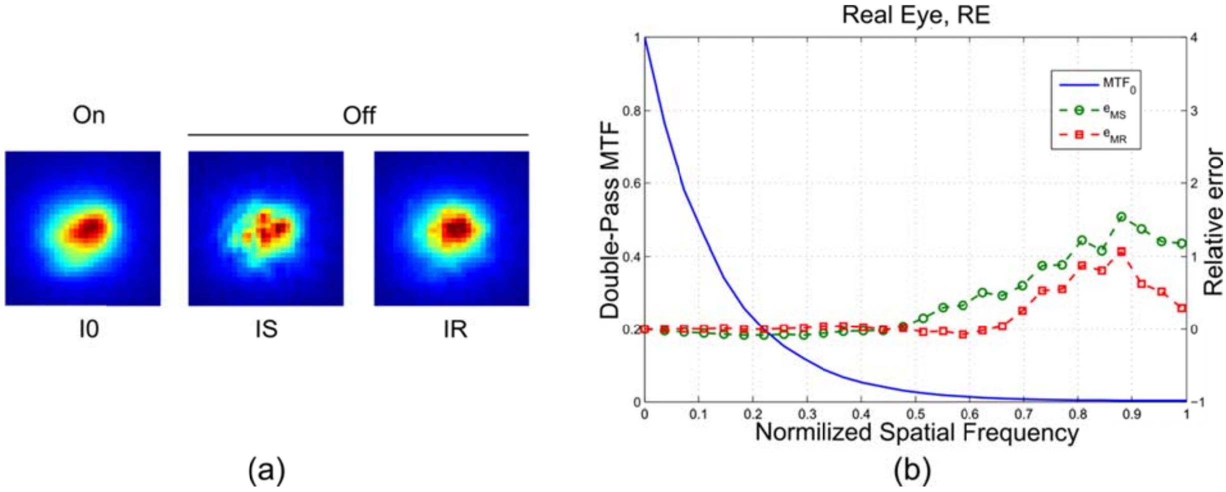

Figure 2. a): Reference (I0), full (IS), and reduced (IR) speckle image for the artificial eye. b): Double pass MTF of the reference image (continued curve, left axis) and relative errors for IS (e_{MS}, discontinued line with circles, right axis) and IR (e_{MR}, discontinued line with squares, right axis) for the real eye.

These errors were computed over data for I=IS and IR relative to I0 using the radial profile of theirs MTF up to the cut-off frequency of the system (vc=44.75cyc/deg).

3. Results

Figure 2-a shows false coloured cropped (32×32pixels) versions of the reference image I0, the full-speckled one IS and the image with reduced speckle IR for the artificial eye. Visual inspection of images reflects lower speckle in IR than in IS and a tendency of the former to the shape of the reference case. The values of SC and $\bar{e}_M$ in table 1 confirms the speckle reduction for both the AE and RE.

The MTF for the real eye plotted in figure 2-b indicates that higher frequencies are the more affected by speckle and that this noise can alter the calculation of the effective cut-off of the eye. For instance, looking for the frequency at which the MTF had a value of 0.01, it goes from 0.658 to 0.601 in terms of vc for IS and IR, respectively. This last value is closer to 0.605, the one obtained for I0, which shows that there deviations in the MTF due to speckle can be corrected when the method is applied. The affectations of higher frequencies also influence the computation in the Strehl ratio; as computed as a ratio between areas, lower frequencies have more weight in the calculation of this parameter. Errors e_{SS} in table 1 reflects that the presence of speckle did not have a critical impact in the Strehl ratio since it remained lower than 5% for all cases. However, data for IR present a lower relative error than those for IS.

Table 1. Speckle contrast (SC), mean relative error of MTF ($\bar{e}_M$), and relative error of the Strehl ratio (e_S) for the artificial (AE) and real eye (RE). Sub-indexes S and R refer to the full and reduced speckle images, respectively.

Subject	**SC_S / SC_R**	**$\bar{e}_{MS}$ / $\bar{e}_{MR}$**	**e_{SS} / e_{SR}**
AE	0.103 / 0.078	1.070 / 0.155	0.042 / 0.011
RE	0.176 / 0.144	0.042 / 0.011	0.021 / 0.013

4. Conclusions

We confirmed that speckle can be reduced in double-pass images by inducing periodic defocuses of small magnitude with a tunable lens. The speckle contrast and the relative errors in the MTF and Strehl ratio presented a lower magnitude when the method was applied. The results suggest that deviations from the reference images were decreased, which suggest that this method to reduce speckle can be used in double-pass systems when measuring the eye´s optical quality. Compared with other methods relying in motors and broad-frequency sources for breaking speckle, the use of liquid lenses could results advantageous since they do not produce vibrations in the system that can be perceived by patients and, with the time, misalign optical elements, without increasing the price of the system. Taking advantage of the fact that the eye produces speckle patterns varying in time, we consider that the use of frequencies higher than 7Hz could increment the number of uncorrelated patters and thus increase the magnitude of the reduction. Finally, we believe that this solution could be also applicable for Hartmann-Shack systems; however, a further study should be performed in this respect.

5. Acknowledgements

This study was supported by the Spanish Ministry of Science and Innovation with the project grant DPI2011-30090-C02-01. Carlos E. García-Guerra acknowledges a fellowship from the Doctorate program EuroPhotonics. The authors thank Ferran Sanabria for his help with the experimental platform.

References

[1] Santamaría J, Artal P, Bescós J. Determination of the point-spread function of human eyes using a hybrid optical-digital method. *J. Opt. Soc. Am. A*. 1987 June; **4**(6):1109–1114.

[2] Güell JL, Pujol J, Arjona M, Diaz-Douton F, Artal P. Optical Quality Analysis System; Instrument for objective clinical evaluation of ocular optical quality. J Cataract Refract Surg. 2004 July; **30**(7):1598–1599.

[3] Marcos S, Burns SA, Chang J. Model for cone directionality reflectometric measurements based on scattering. *J. Opt. Soc. Am. A*. 1998 Aug; **15**(8):2012–2022.

[4] Hofer H, Artal P, Singer B, Aragón JL. Dynamics of the eye's wave aberration. *J. Opt. Soc. Am*. 2001 Mar; **18**(3):497–506.

[5] Hampson KM, Chin SS, Mallen EAH. Binocular Shack–Hartmann sensor for the human eye. *Journal of Modern Optics*. 2007; **55**(4-5):703–716.

[6] Goodman JW. Some fundamental properties of speckle. *J. Opt. Soc. Am*. 1976 Nov; 66(11):1145–1150.

[7] Kelly DP, Ward JE, Gopinathan U, Sheridan JT. Controlling speckle using lenses and free space. *Optics letters*. 2007 Dec; **32**(23):3394-3396.

[8] Yu CC, Matsubara I, Dallas WJ. Speckle noise reduction for digital holography using longitudinal shifting. Conference on Digital Holography and Three-Dimensional Imaging. 2012 Apr 28-May 12; Miami, Florida United States.

[9] Sanàbria F, Díaz-Doutón F, Aldaba M and Pujol J. Spherical refractive correction with an electro-optical liquid lens on a double-pass system. *J. Europ Opt. Soc. Rap. Public*. 2013 Sep; **8**:13062 1-4

[10] Vilaseca M, Padilla A, Ondategui JC, Arjona M, Güell JL, Pujol J. Effect of laser in situ keratomileusis on vision analyzed using preoperative optical quality. *J. Cataract. Refract. Surg*. 2010 Nov; **36**(11):1945-53