Phase Randomization for Holographic AR Display

Fergal Shevlin, Ph.D.

DYOPTYKA, Dublin, Ireland. fshevlin@dyoptyka.com

Abstract: *Holographic augmented reality (AR) displays using phase-only spatial light modulators (SLMs) with coherent illumination suffer from objective and subjective speckle that degrades image quality. Partial spatial coherence from an extended source of diameter D_s reduces speckle but, because the partially-coherent point spread function (PSF) inherits the source profile, also increases retinal blur. We describe a phase-randomizing deformable mirror (DM) whose smooth deformations have spatial wavelengths $\Lambda \gg \lambda$, so it generates many statistically independent wavefront realizations within the eye's integration time while preserving the $\sim 3^\circ$ angular divergence appropriate for efficient coupling into AR waveguides. The speckle–blur trade-off defines a useful range of D_s, bounded below by the DM's transverse correlation length and above by the application's retinal blur tolerance. Within this range, $D_s \approx 100$–$200\,\mu\mathrm{m}$ yields measured speckle contrast reductions from $31\,\%$ to $14\,\%$ without perceived loss of legibility.*

Keywords: holographic display; speckle; image blur; deformable mirror; moving diffuser; augmented reality; partial coherence; étendue

1. Partial coherence

A phase-only SLM reconstructs a computer-generated hologram (CGH) by diffracting a reference wavefront from a *coherent point source.* Image quality problems evident in Fig. 1 include objective speckle within the hologram, subjective speckle arising from surface roughness in optical system, and inhomogeneity of intensity across the field due to different paths taken through the optical system [1].

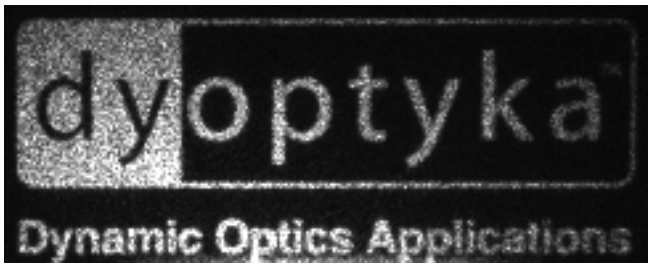


Figure 1. CGH from liquid crystal on silicon (LCoS) SLM using a coherent point source, speckle contrast $C_S = 31\%$.

A common mitigation is to use instead a *partially-coherent extended source* of time-averaged intensity profile $g_s(\mathbf{r}) = \langle |E(\mathbf{r},t)|^2 \rangle_\tau$ and diameter D_s [2]. Each instantaneous realization presented to the SLM remains a coherent wavefront and the superposition over the eye's integration τ smooths the speckle patterns produced by successive realizations. Because the PSF of the partially-coherent reconstruction inherits the spatial profile of g_s, speckle is reduced but blur is increased. Hence the choice of D_s is critical to image quality.

2. Source requirements

Laser diodes are compact, directional, energy efficient, narrow linewidth sources and there are various means to increase their spatial extent and to reduce their spatial coherence. For the application being considered, requirements to be satisfied include: an instantaneous coherent wavefront at the SLM; time averaged wavefront similar to the reference assumed for CGH encoding; fast enough to generate many independent wavefront realisations within the eye's integration period $\tau \sim 20$–$50\,\mathrm{ms}$; and narrow angular extent for efficient coupling into AR optical elements.

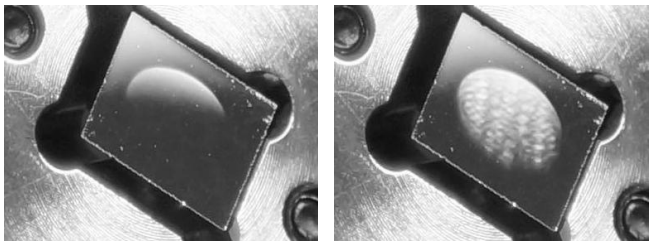


Figure 2. DM inactive and active. Superpositions of standing and travelling waves randomize phase at frequencies up to $\sim 1\,\mathrm{MHz}$.

3. Candidate approaches

A convenient approach is to direct laser illumination into a spot of diameter D_s onto a diffuser which moves such that multiple random phases are generated within τ. However diffuser structures with sizes similar to the illumination wavelength λ result in diffraction at angles exceeding those required for efficient coupling.

Our company has developed a phase randomizing deformable mirror technology shown and further described in Fig. 2. The spatial wavelengths Λ of its smooth deformations are orders of magnitude longer than λ so there is no wide angle diffraction. Angular divergence from a spot of diameter D_s is typically configured to be approx. 3° which is appropriate for efficient coupling.

The DM's smooth deformations have a transverse phase autocorrelation that, for a single sinusoidal mode of spatial wavelength Λ, follows $\cos(2\pi\,\delta r/\Lambda)$ and first crosses zero at $\delta r \approx \Lambda/4$. For the broadband superposition of standing and travelling waves shown in Fig. 2, destructive interference between modes drives this decorrelation length further below $\Lambda/4$. We denote it d_c. Spots of diameter $D_s \lesssim d_c$ see a near-uniform

instantaneous DM phase; equivalently, the SLM-plane mutual coherence function $\Gamma(\mathbf{r}_1, \mathbf{r}_2) = \langle U(\mathbf{r}_1)\, U^*(\mathbf{r}_2)\rangle_\tau$ stays close to unity for $|\mathbf{r}_1 - \mathbf{r}_2| \lesssim d_c$. The time-averaged source then remains effectively coherent and point-like, no decorrelation between successive realizations is available, and d_c sets the minimum useful illumination spot diameter.

4. Speckle

Although the DM can generate independent wavefront realisations at frequencies far exceeding those of alternative approaches, there is a limit to the speckle reduction that can be achieved. The partially-coherent wavefront at the eye pupil has angular extent $\theta_i \approx M_a D_s / f_c$, with M_a the SLM-to-eye angular magnification and f_c the collection-lens focal length. The Van Cittert–Zernike theorem gives a transverse pupil-plane coherence length $\ell_c \sim \lambda/\theta_i$; the number of statistically independent coherence cells captured by the pupil of diameter D_{pupil} is $N \sim (D_{\mathrm{pupil}}/\ell_c)^2$, and retinal speckle averages to

$$C_S \;\approx\; 1/\sqrt{N} \;\approx\; \theta_d/\theta_i, \tag{1}$$

with $\theta_d \approx \lambda/D_{\mathrm{pupil}} \approx 0.6\,\mathrm{arcmin}$ the eye's diffraction-limited resolution [1]. At $D_s = 100\,\mu\mathrm{m}$, $f_c = 50\,\mathrm{mm}$, $M_a \sim 1$, $\theta_i \approx 7\,\mathrm{arcmin}$, $N \approx 130$, and the floor for SLM-pixel speckle is $C_S \gtrsim 9\,\%$. This can be further increased by optical system surface roughness such that the speckle seen in Fig. 3 is typical.

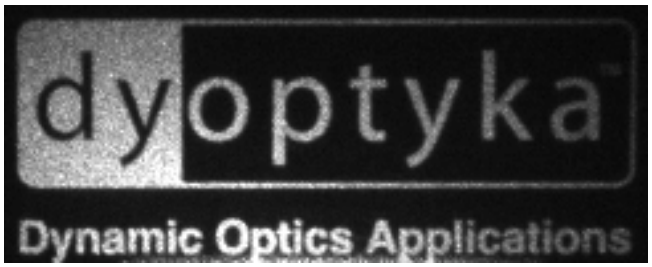


Figure 3. Same CGH, SLM, and coherent point source as Fig. 1 but with active DM to achieve $C_S = 14\%$.

5. Blur

The partially-coherent imaging law for a shift-invariant SLM-to-retina relay with mutually incoherent source points on time-average is [4]

$$I_{\mathrm{out}}(\mathbf{r}) \;\approx\; g_s(\mathbf{r}) \otimes |h(\mathbf{r})|^2, \tag{2}$$

where h is the coherent point-source impulse response of the SLM-to-retina chain. Equations (1) and (2) together expose the central design tension: the same g_s that decorrelates speckle by widening θ_i also widens the retinal PSF, so speckle suppression and blur are coupled through D_s and cannot be independently optimised. The PSF inherits the spatial profile of g_s, so retinal blur scales with the same θ_i. At $D_s = 100\,\mu\mathrm{m}$ the retinal blur is $\theta_i \approx 7\,\mathrm{arcmin}$ — acceptable for typical AR text rendered at a few arcminutes per character but coarser than foveal acuity.

A lower bound on D_s is set by the DM decorrelation length d_c (§3): at $D_s \lesssim d_c$ no decorrelation between successive realizations is available. An upper bound arises from the application's retinal angular blur tolerance $\Delta\theta_R$. The useful operating window is

$$d_c \;\lesssim\; D_s \;\lesssim\; D_{\mathrm{blur}} \;\equiv\; \frac{f_c\,\Delta\theta_R}{M_a}, \tag{3}$$

with empirical optima reported around $D_s \approx 100$–$200\,\mu\mathrm{m}$ [3].

Both a diffuser and DM at matched D_s should sit on the same speckle–blur curve; the distinction between approaches lies not in the curve itself but in whether the chosen D_s can be reached without unacceptable loss of étendue.

6. Conclusions

A phase-randomizing deformable mirror provides the partial coherence required to suppress speckle in holographic AR displays while preserving the narrow étendue needed for efficient waveguide coupling. Because $\Lambda \gg \lambda$, the DM introduces none of the wide-angle diffractive loss inherent to wavelength-scale moving diffusers, and many independent realizations occur within the eye's integration period τ. Equations (1)–(3) frame the design problem as the choice of a single source diameter D_s on a speckle–blur curve common to all phase-randomization approaches; the DM's distinguishing property is that the useful portion of that curve is accessible to it. At $D_s \approx 100$–$200\,\mu\mathrm{m}$, objective speckle contrast falls from $31\,\%$ to $14\,\%$ (Figs. 1 and 3), consistent with the partial-coherence floor of Equation (1) elevated by the surface-roughness contribution noted in §4. The same operating point should transfer to metasurface- and surface-relief-waveguide AR architectures [5, 6], where preserving étendue under aggressive speckle suppression is the central illumination-side constraint.

References

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