Adaptive phase distortion correction in strong speckle-modulation conditions

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Received July 3, 2002

We introduce beam-quality metrics for adaptive wave-front control that permit estimation of the degree of laser beam energy concentration on a remotely located extended object based upon the backscattered wave intensity distribution at the receiver. A 37-control-channel adaptive optics system with phase correction of the output wave capable of operating in the presence of speckle-field-induced strong intensity modulation is presented. System operation is based on optimization of the speckle-field-based metric by the stochastic parallel gradient descent technique. Results demonstrate that adaptive wave-front correction using speckle-field-based beam-quality metrics can significantly improve laser beam concentration on extended objects. © 2002 Optical Society of America

OCIS codes: 010.0010, 010.1080, 230.3990.

Coherent radiation scattering off an extended object surface located in an optically inhomogeneous medium leads to the formation of a backpropagating wave with a highly spatially nonuniform intensity and phase distribution, known as a speckle field. For scattering off objects with large-scale surface roughness (both the roughness correlation radius and its amplitude substantially exceed the light wavelength), the development of a speckle field occurs over relatively short distances that are much shorter than the typical propagation distance between object and receiver telescope. Backpropagation of the speckle field to the receiver (or transceiver) telescope over a path with random refractive-index inhomogeneities results in additional wave-front phase and amplitude distortions. Both distortion types, those induced by scattering off the object surface and those induced by the propagation medium, are superimposed at the receiver aperture in a complex fashion. Knowledge of the phase aberration component that results exclusively from the medium’s inhomogeneities is highly desired for many adaptive optics application, including laser illumination, active imaging, target-in-the-loop adaptive optics, and laser technology (welding, cutting). In these adaptive system types wave-front control is applied to the outgoing (transmitted) wave to achieve better concentration of the laser beam’s energy onto the object surface. However, direct extraction of the propagation-related phase aberration component presents a difficult problem for conventional adaptive optics techniques based on direct phase reconstruction of the wave phase from wave-front sensor data.

In this Letter we propose and demonstrate a target-in-the-loop adaptive optics system capable of operating in the presence of strong speckle-field modulation that permits efficient laser beam energy concentration onto extended object surfaces. This method is based on the known dependence of speckle-field statistical properties on the laser beam intensity distribution upon the extended object. Specifically, it follows from the Van Cittert–Zernike theorem that the characteristic speckle-field spatial correlation radius (speckle size) \( a_s \) at the receiver plane is inversely dependent on the characteristic beam size \( b \) at the object surface: \( a_s = \lambda L / b \), where \( L \) is the propagation path length and \( \lambda \) is the wavelength. This simple (within an order of magnitude) relation suggests that the characteristic speckle size at the receiver plane can be used as a laser beam quality metric \( J_s \) (speckle metric) to characterize beacon brightness (laser beam concentration on the object surface). Correspondingly, adaptive wave-front phase distortion correction of the outgoing wave can be achieved based on direct speckle-metric optimization techniques, for example, using the recently proposed stochastic parallel gradient descent (SPGD) optimization method.

Beam-quality metrics based on the statistical characteristics of speckle-field-induced photocurrent fluctuations registered by a single photodetector were considered in earlier publications. The principal problem with the use of these metrics arises from their strong sensitivity to object motion. The beam-quality metric \( J_s \), introduced here is sufficiently less sensitive to object motion, as it depends on the spatial characteristics of the speckle field.

The scheme of the experimental setup is shown in Fig. 1. A linearly polarized laser beam from an argon laser (\( \lambda = 0.514 \, \mu m \)) was expanded to a diameter of 10 mm, corresponding to the aperture size of the deformable mirror (DM). The deformable mirror (from OKO, Inc.) consists of a chip with a silicon nitride membrane coated with aluminum, forming a mirror attached to the substrate. The membrane shape is electrostatically controlled by voltages applied to the 37 hexagonally shaped control electrodes.

The optical relay system is composed of lens \( L_1 \) and a transmitter telescope (from Celestron). The beam is reflected from the deformable mirror, expanded to an 80-mm diameter, and focused onto the rough surface of an extended target located approximately 5 m from...
Fig. 1. Scheme of the target-in-the-loop adaptive system experimental setup. The photos at the bottom are a, objects used in the experiments (the distance between holes on the optical bench is 1″ (2.54 cm)); b, intensity distribution on the object surface with adaptive system feedback on; c, same as in b but for feedback off. The scales in b and c are the same. The diameter of the beam in photo c is ~5 mm. BS, beam splitter.

the telescope pupil. An aluminum half-cylinder and an aluminum half-sphere 5 cm in diameter (Fig. 1a) as well as the surface of the optical table were used as extended targets for the adaptive target-in-the-loop experiment. The speckle field scattered off the target surface was registered by the receiver system. The receiver system included a Celestron telescope (similar to the one used as the transmitter) and a digital 8-bit DALSA CCD camera (CCD1) with 128 × 128 pixel resolution and an 880-frame/s rate. The registered images of the speckle field (shown in Figs. 2a and 2b) were used for computation of the speckle-field-based beam-quality metric $J_s$.

The beam-quality metric $J_s(t_n)$ was calculated using a sequence of speckle-field intensity distributions $I_n(r)$ captured at times $t_n = n\Delta t$ ($n = 0, 1, \ldots$), where $\Delta t = 0.01$ s was the time interval between subsequent frames:

$$J_s(t_n) = \int E_n(r) d^2 r,$$

where $E_n(r) = |\nabla^2 [\text{sign}(I_n(r) - \bar{I}_n)]|$.  

The function $E_n(r)$ defines an edge-indicator map (modulus of the Laplacian operator $\nabla^2$) applied to the speckle-field intensity deviation from the threshold level $\bar{I}_n$ (sign operator). The selected threshold level $\bar{I}_n$ corresponded to the aperture-averaged (mean) speckle-field intensity value. Note that any operator that enhances the speckle-pattern contrast can be used in Eq. (1) in place of the sign operator. As seen in Figs. 2c and 2d, the edge-indicator map contains speckle contours, so the metric $J_s$ in Eq. (1) represents the total contribution of edges within a registered speckle pattern. Having a defocused beam on the object surface (see the photo in Fig. 1c) corresponds to a small characteristic speckle size at the receiver aperture (Fig. 2a), and correspondingly a dense edge-indicator map pattern (Fig. 2c) and a larger $J_s$ value. In contrast, the sharply focused beam in Fig. 1b corresponds to large speckles, a sparse edge map (Fig. 2d), and a small $J_s$ value.

Metric (1) was used for adaptive control of the deformable mirror by the SPGD optimization technique. The control voltages $u_{j}^{(n)}$, $j = 1, \ldots, 37$ applied to the deformable mirror electrodes (in the range 0–180 V) were updated at each $n$th iteration of the SPGD metric $J_s(t_n)$ minimization:

$$u_{j}^{(n+1)} = u_{j}^{(n)} + \gamma^{(n)} \delta J_n^{(n)} \text{sign}[\delta J_n^{(n)}] \text{sign}[\delta u_{j}^{(n)}]$$

(2)

where $\gamma$ is a gain coefficient and $\{\delta u_{j}^{(n)}\}$ and $\{\delta J_n^{(n)}\}$ are, correspondingly, the random perturbations applied in parallel to the mirror electrodes and the metric change resulting from these perturbations.

For direct estimation of the beam intensity concentration on the object surface, an additional CCD camera (CCD2) was placed in a plane conjugate to the object’s surface. The intensity $I_n^o(r)$ registered by camera CCD2 is proportional to the intensity on the object’s surface. Cameras CCD1 and CCD2 were synchronized to simultaneously measure the intensity distributions of speckles $I_n(r)$ and object $I_n^o(r)$. The intensity $I_n^o(r)$ was used to calculate the well-known sharpness function (metric) $J_2(t_n)$ (Ref. 13):

$$J_2(t_n) = \int (I_n^o(r))^2 d^2 r.$$ 

Maximization of the metric $J_2$ corresponds to localization of the laser beam energy. By connecting either computer PC1 or PC2 to the deformable mirror it was possible to compare the performance of the adaptive optics system while minimizing the speckle metric $J_s$ or with the same system maximizing $J_2$.

Adaptive system efficiency was characterized using of the self-induced aberration compensation technique described in Ref. 8. In this method random phase distortions are introduced by the adaptive system itself.
structure inside the receiver aperture that contains many speckles (anisoplanatic beacon conditions). An adaptive speckle-metric-based system reduces the beam size on the object to the point where there are only a few speckles (ideally only a single speckle) inside the receiver aperture. In this case the beacon itself can be considered as a coherent light source (isoplanatic beacon condition). Note that even in isoplanatic conditions the beam width on the object can be noticeably larger than the diffraction-limited beam size because of the presence of residual phase distortions. These phase distortions cannot be compensated for by use of a speckle-metric-based adaptive system, as they do not result in the multispeckle intensity patterns necessary for speckle-metric system operation. In contrast, conventional adaptive optics is efficient exactly in isoplanatic beacon conditions and can be used to compensate for these residual phase distortions. Thus the speckle-metric-based adaptive technique can be used for precompensation of phase distortions under conditions where conventional adaptive techniques typically fail.

A combination of the conventional and speckle-metric-based adaptive techniques may provide effective target-in-the-loop adaptive optical control in the presence of strong speckle-field modulation.

This work was supported in part by the U.S. Joint Technology Office (grant JTO-02-602-18). M. A. Vorontsov’s e-mail address is mvorontsov@arl.army.mil.

References

14. We consider here the rather typical scenario where speckle statistics (characteristic speckle size) does not significantly change during transmission.