Pupil Phase Encoding for Mitigation of Laser-induced Saturation in Imaging Sensors

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Abstract – Pupil phase encoding can mitigate the harmful effects of unwanted laser illumination. A pupil phase element can spread out the focused beam, avoiding detector saturation. We consider different classes of phase elements for this application.

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1. Introduction

Digital imaging sensors can be compromised by laser beams pointed directly at them. For very high laser intensities, physical damage may actually compromise the long-term performance of the sensor. For moderate intensities, the incoming laser beam may obscure important parts of the scene while the beam is in the field of view. In this work, we assume that the laser beam originates at a significant distance from the camera, allowing the field incident at the sensor to be modeled as a plane wave overfilling the imaging sensor lens. We further assume that the lens is diffraction limited and focused near infinity. Under these conditions, much of the energy is incident on a single pixel, leading to a highly saturated condition.

We consider the use of wavefront coding [1] where a phase element is introduced at the pupil plane to spread the energy into a larger area. The overall effect is an attenuated laser beam spot, but the resultant image is blurred and requires post-detection processing to restore the image quality. We consider three classes of phase masks: cubic, pseudo-random, and pupil phase engineered (PPE) masks. We present numerical and laboratory results for the case of a cubic mask and also present preliminary discussions of the use of random and more general designs of PPE masks.

2. Analysis in the presence of aliasing

The key parameters to model the expected laser attenuation by a phase mask are F/# and sensor pixel size. These two parameters determine how much aliasing is in the system and have a strong effect on the observed attenuation. Since most optical systems are aliased, the intensity of the brightest pixel will depend on the position of the Airy disk relative to the CCD pixel grid. We are interested in the case where the peak of the Airy disk lines up exactly with the center of a sensor pixel creating the highest possible digital count at the detector. We simulate the spot created at the detector and define the attenuation caused by diffraction of a standard lens as,

$$A_s = \frac{\sum_{x,y} I_s(x,y)}{\max_{x,y} I_s(x,y)}$$

(1)

where the $I_s$ represents the image in a standard diffraction-limited system. Note that the max operator corresponds to the brightest pixel after searching over all possible diffraction-limited system and the attenuation is similarly defined as,
\[ A_r = \frac{\sum_{x,y} I_c(x,y)}{\max_{x,y} I_c(x,y)} \]  

where the \( I_c \) denotes the image in a wavefront coded system. Once again we account for aliasing by searching for the shift that gives the maximum value. The attenuation of interest is measured relative to the standard attenuation and is given by,

\[ r = \frac{A_c}{A_s}. \]

The quantity \( r \) is the reciprocal of the Strehl ratio of the wavefront coded system with respect to the conventional diffraction-limited system, approaching \( A_c \) for very small spots. However, in practice, even diffraction-limited systems spread some of the energy out of the brightest pixel. We desire to achieve a large value of \( r \) so that bright spots are strongly attenuated. Note that this is the worst case attenuation over all possible aliased versions of the wavefront coded point spread function.

3. Results for cubic phase mask

We performed both numerical and laboratory simulations using a circular aperture cubic phase mask. For both the standard and cubic systems, we simulated the detector downsampling using a sample rate determined by the ratio of the CCD pixel size to the F-number. Results for a system with F/\# = 2.8 are given in Figure 1 as a function of CCD pixel size. The result is shown for a number of different cubic thicknesses. Thicker cubic masks produce more blurring and hence more attenuation, however, the quality of the restoration in the presence of noise degrades.

The plot in Figure 1 shows that an attenuation of 100 occurs for a pixel size of approximately 3 microns when using a cubic with 57 waves across the x-axis. The model shows an attenuation of 50.1 for the case of a 4.65 micron pixel and is consistent with our laboratory measurements of \( A_c \) with a 2.8 F-number lens and a Sony ICX-205AL sensor having 4.65 micron pixels. The attenuation for a sensor with 7.4 micron pixels is approximately 28.1 for a 57 wave cubic. Predictions are provided also for stronger cubic phase masks. In practice, image restoration will be compromised by noise and the final image quality must be evaluated taking the image analysis task into account.

![Figure 1](image.png)

**Figure 1.** Plot of laser attenuation cubic phase encoded F/\# = 2.8 imaging system. Results are given for cubic phase masks of various phase thicknesses: dark line 57 waves, grey line 76 waves, and light grey line 100 waves.

4. Random phase masks

We have initiated a study of the use of pseudo-random phase mask with a high degree of correlation in adjacent
sample values. The phase mask is generated by starting with independent random (sampled) values in the range \([-1,1]\). Correlation is enforced by attenuating the 2-D spectrum of the array of independent random variables; a weighting function generated by a power law is used as a point-wise attenuation factor. Three parameters control the final phase mask: 1) the exponent of the power law, 2) a scaling factor for the coordinate space defining the weighting function, and 3) an amplitude parameter to control the strength of the phase mask. The pseudo-random phase mask approach appears competitive with other results obtained for the cubic phase mask, but does not demonstrate dramatic superiority over the cubic phase mask. The primary limitation of the pseudo-random phase approach lies in the inherent ill-conditioning of the blurring operator. Work is underway to provide an objective comparison between the cubic phase and random phase approaches.

5. Pupil phase encoding design approach

We propose the study of pupil phase masks that can shape the system point spread function such that the energy is spread more or less evenly across the image plane, while allowing the signal to be sufficiently restorable in the presence of noise. Our previous work on pupil phase engineering [3,4,5,6] provides a numerical framework and a starting point to optimize the design of general pupil-phase masks with respect to various performance criteria. One potential approach being considered is to jointly maximize the MTF while minimizing the Strehl ratio Eq. (3), with respect to a certain number of phase design parameters, e.g. coefficients of a finite Zernike expansion. Here, an additional constraint on the phase function may be enforced to diminish wavelength dependence. A second approach where the axial shape of the PSF can be tailored using multi-zone Toraldo filters [2] will also be considered.

6. Discussion

Pupil phase encoding can provide attenuation of laser induced detector saturation. The amount of expected attenuation is strongly dependent on the effective numerical aperture of the system and the size of the detector pixels. Numerical and laboratory studies were provided that give numerical predictions of the amount of attenuation for the specific case of a cubic phase encoded pupil. We also present preliminary investigations of random phase mask and a more general pupil phase engineering design method.


