New image processing challenges for jointly designed electro-optical imaging systems

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Abstract— **Still-image processing algorithms are tailored to and depend crucially upon the properties of the class of images to which they are applied, for instance natural images in consumer digital cameras, medical images in fMRI machines, and binary text images in some photocopiers. We describe a new and possibly very important class of images and tasks for which traditional algorithms seem ill-suited, and for which new algorithms and general methods and concepts are required. This new class of images arises in imaging systems designed through new, joint optimization methods where the optics and the image processing are designed simultaneously in order to yield a high-quality digital image. These new design methods yield intermediate optical images that have unusual spatial, noise and chromatic properties ill-served by traditional image methods. Moreover, these new images present a number of novel challenges in image processing hardware implementations such as constrained space-variance. We describe these briefly new, joint methods for designing digital-optical imaging systems, characterize the intermediate optical images they yield, and some of the digital image processing challenges for producing high-quality still images from these sensed optical images.**

I. INTRODUCTION

The last few decades have ushered in an era of imaging where optical images are sensed by digital sensors and displayed on digital devices. Today, solid-state photodetector arrays have almost completely supplanted traditional silver-halide-based cameras, for instance. Moreover, nearly every such imaging system employs some image processing, often to correct defects in the optical image or the sensor itself, such as denoising algorithms to reduce sensor noise and deconvolution algorithms to restore lost contrast due to mis-focussed optics. These algorithms are appropriate for optical images in traditional imaging systems, where the (intermediate) optical image is high quality.

However, in the vast majority of of current and future imaging applications, there is no need for the intermediate optical image to "look good"—only for the *final*, digitally processed image to "look good." Based on that insight, some system designers have recently developed new methods and software for jointly designing the optics *with* image processing based on an end-to-end of full-system merit function[1]. As we shall demonstrate this new design methodology is far more powerful than the traditional sequential design of optics *then* image processing. Much of the broad concepts of such end-to-end optimization are described in [2] which describes an imaging system as an information channel. Designing such systems involves *joint optimization* of the optics, detector, and digital image processing subsystems [1]. Systems designed in this fashion yield intermediate optical images quite unlike those arising in imaging systems designed by tradition sequential methods, and as such these new systems require new classes of image processing algorithms and present new theoretical and implementation challenges.

In this paper we briefly describe a unified framework for describing and evaluating digital-optical imaging systems designed this way. We highlight three examples of non-traditional digital-optical imaging systems and the unique image processing requirements for each. Finally, we summarize the challenges and opportunities for image processing to transition these new systems from exotic examples to mainstream imaging systems.

II. JOINT DESIGN OF DIGITAL-OPTICAL IMAGING SYSTEMS

Recall that the first step in the traditional, sequential, approach to designing electro-optical imaging systems is to design a lens system so as to form the highest quality optical image possible, where quality is quantified by traditional optical merit functions such as RMS spot size or measures based on the modulation transfer function. Designing lens systems to achieve these goals involves optimizing the shapes, spacings, and materials of lens elements to focus light rays from a point source object into a single spot [3], [4]. This highly nonlinear optimization process requires sophisticated optical design tools. The second step in the approach is to design the image processing algorithms, typically to correct defects and aberrations introduced by the optical system. In contrast, the new joint approaches to designing electro-optical imaging systems is to design the lens and image processing *jointly* so as to optimize an end-to-end merit function.

The first step in this new approach is to characterize the ideal final digital image. We denote the ideal projected image of a two-dimensional object at a particular wavelength λ and distance z_o from the camera by $s_{obj}(\mathbf{x}', z_o, \lambda)$, where $\mathbf{x}$ represents the two-dimensional image coordinates. The ideal optical image of such a source luminance function is a band-limited (free of aliasing) and sampled two-dimensional projective transformation of the object radiance represented by $s_{ideal}(\mathbf{x}, \lambda)$, where the image coordinates are defined by a combination of the imaging system's focal length f and object distance z_o.

The optical lens system projects a real inverted image onto a planar digital sensor. The optics of the imaging system affects this two-dimensional luminance function according to

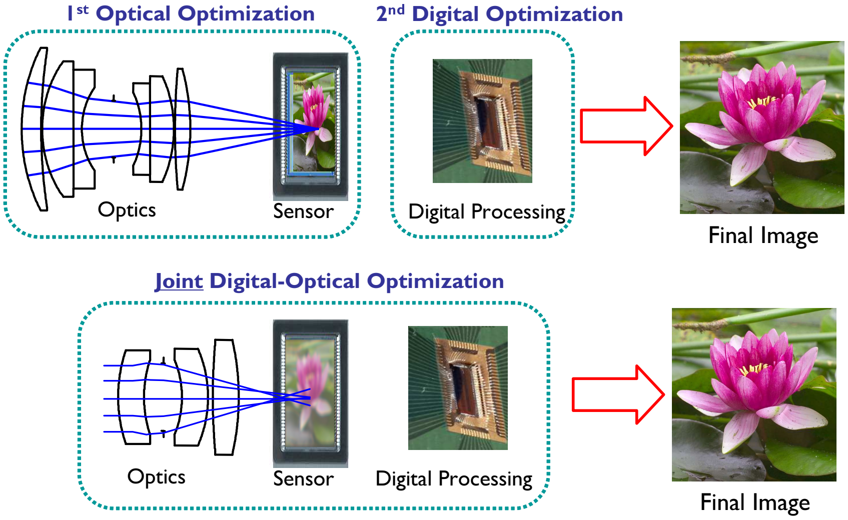

Fig. 1. The top diagram shows the traditional image system design method whereby first the optical subsystem is optimized using optical figures of merit and then the image processing subsystem is subsequently optimized. The bottom diagram shows the novel end-to-end design method whereby the entire digital-optical system is optimized in a joint fashion. The joint approach generates optical subsystems appear sub-standard according to optical figures of merit, but after image processing show performance matching or even besting that of the traditional method.

the spatially varying convolution integral

$$s_{opt}(\mathbf{x}, \lambda) = \int s_{ideal}(\mathbf{x} - \tilde{\mathbf{x}}, \lambda) h_{opt}(\mathbf{x}, \tilde{\mathbf{x}}, \lambda, z_o) d\tilde{\mathbf{x}}, \qquad (1)$$

where $h(\mathbf{x}, \tilde{\mathbf{x}}, \lambda, z_o)$ is the optical system's spatially varying point-spread function (PSF) and the vector $\tilde{\mathbf{x}}$ represents the convolution slack variables. For simplicity, we represent this convolution operation in vector notation as $\mathbf{s}_{opt}(\lambda) = \mathbf{H}(\lambda, z_o)\mathbf{s}_{ideal}(\lambda))$ where the vectors represent raster samples of the spatial coordinates.

Every lens system's point-spread function depends upon the geometric aberrations. The point-spread function is related via the wavefront-error function known as the Optical Path Difference or OPD function $\Phi(\mathbf{p}, \mathbf{x}, \lambda, z_o)$, where $\mathbf{p}$ represents the two-dimensional coordinates in the exit pupil plane. Incidently, the OPD function is very often the primary means by which optical lens designers evaluate and optimize lens systems. The most traditional optical figures of merit involves some form of the square of the OPD function averaged over the lens exit pupil, e.g., OPD-RMS or geometric spot size.[3], [4]

The optical system's PSF at a particular field location $\mathbf{x}$ is a function of the OPD according to

$$h(\mathbf{x}, \tilde{\mathbf{x}}, \lambda, z_o) \approx \left| \int A(\mathbf{p}, \mathbf{x}) e^{j\Phi(\mathbf{p}, \mathbf{x}, \lambda, z_o)} e^{j2\pi \tilde{\mathbf{x}}\mathbf{p}} d\mathbf{p} \right|^2, \qquad (2)$$

where $\Phi(\mathbf{p}, \mathbf{x}, \lambda, z_o)$ is expressed in terms of the exit pupil coordinates $\mathbf{p}$ and the image location coordinate $\mathbf{x}$. The function $A(\mathbf{p})$ is the magnitude of the exit pupil (most commonly valued either 0 or 1 for opaque or transparent). The function h is based on the magnitude squared of the Fourier transform of the pupil function, $A(\mathbf{p}, \mathbf{x}) e^{j\Phi(\mathbf{p}, \mathbf{x}, \lambda, z_o)}$ [5]. In jointly designed digital-optical imaging systems, this goal of minimizing wavefront aberrations is relaxed to achieve system-level benefits, such as fewer lens elements, shorter optical tract, lower f-number, and so on.

The photodetector array converts the optical image from photons into electrons and then into bits. The ideal image, being bandlimited, is conveniently represented in vector notation as $\mathbf{s} = \int w(\lambda)\mathbf{s}_{opt}(\lambda) d\lambda$, and consists of raster a ordered collection of ideal optical image samples. The weighting function $w(\lambda)$ represents the spectral sensitivity of the photodetector array. Similarly, the sampled point-spread function is denoted $\mathbf{H}(\lambda, z_o)$, which is comprised of the samples of the spatially varying point spread function $h(\mathbf{x}, \tilde{\mathbf{x}}, \lambda, z_o)$.

Finally, the following linear model represents the entire imaging formation process:

$$\mathbf{y} = \int w(\lambda) \mathbf{H}(\lambda, z_o) \mathbf{s}(\lambda) d\lambda + \mathbf{n}, \qquad (3)$$

where $\mathbf{n}$ represents the random noise inherent to the photo-electric transduction.

The final step in the imaging pipeline is the image processing. The goal of imaging processing is estimating the ideally sampled image $\mathbf{s}$ from a captured image $\mathbf{y}$. For a number of mathematical and computational reasons, the quality of the estimated image $\hat{\mathbf{s}}$ should be measured by the mean-square error (MSE) criterion,

$$MSE = \mathcal{E}_{\mathbf{n},\mathbf{s}} \left[\|\hat{\mathbf{s}} - \mathbf{s}\|^2 \right], \qquad (4)$$

where the subscript on the expectation operator $\mathcal{E}$ represents that the expectation is taken over the random noise $\mathbf{n}$ and the signal $\mathbf{s}$. Very often the method for estimating the original image is based on linear filters to restore the image such as the Wiener filters.

The central concept in the joint digital-optical design philosophy is that of minimizing the MSE for the entire imaging system by simultaneously adjusting the entire collection of optical (lens shapes, materials), and digital parameters (filter coefficients), $\mathbf{\Theta}_o, \mathbf{\Theta}_d$. Figure 1 provides an overview comparison between the traditional and the joint digital-optical design approaches.

The optical subsystems resulting from this joint design process often have properties which would be deemed quite poor under the traditional optical merit functions. Yet, when evaluating from an end-to-end perspective, the jointly designed digital-optical imaging systems achieve significantly improved capability at a lower system cost (fewer optical elements), shorter optical tract, lower f-number or larger field of view compared to otherwise equivalent traditional sequentially designed counterparts.

The key ingredient in these digital-optical imaging systems is the image processing. While the required image processing is conceptually similar to those in well-understood image processing problems, the non-traditional optical properties of the optical subsystems necessitates innovative image processing. In the next section we highlight three properties of digital-optical imaging systems which present unique challenges for image processing research.

III. SOME NON-TRADITIONAL OPTICAL IMAGING SYSTEMS

The novel optical subsystems arising in joint digital-optical design posses unusual optical characteristics and demand specialized image processing. In this section, we highlight three exemplifying properties of non-traditional computational optical subsystems; namely, point-spread functions that are large, spectrally, or spatially variant.

A. *Large coded PSFs*

The last few years has seen several examples aperture-coded or wavefront-coded optical imaging systems. Such systems engineer either the wavefront error function $\Phi(\mathbf{p}, \mathbf{x}, \lambda, z_o)$ or the aperture function $A(\mathbf{p}, \mathbf{x})$ to achieve system level benefits. The most successful example of such coding is the wavefront coding (WFC) pioneered by CDM Optics [6], [7], [8]. The WFC method inserts non-standard lens surfaces or phase plates into an optical systems to achieve extended depth-of-field. The technique works by creating a large optical PSF which is less sensitive to object depth z_o and hence defocus [6]. To achieve this system-level benefit, however, the optical PSF is significantly larger than that of a traditional well-focussed optical system. This creates blurry images which require subsequent digital sharpening. Figure 2 shows an example comparing the through-focus PSF of a traditional optical system and that of a cubic-phase plate EDoF system. In addition, notice that the EDoF system has very non-traditional PSF shape. Other researchers have identified alternate coding strategies to achieve EDoF imaging [9], [10].

All of these coding strategies inherently increase the size of the PSF (sacrifice modulation transfer function (MTF) at low spatial frequencies). Enabling the real-time image processing for such large PSFs will require novel sharpening implementations which consider the specific properties of the optical system to provide high quality imagery. For example, hardware filtering may require very low bit-precision and filter size to minimize implementation complexity. Also, better models of evaluating the perceptual impact of incorrect filter sizes would improve our understanding of the necessary processing complexity.

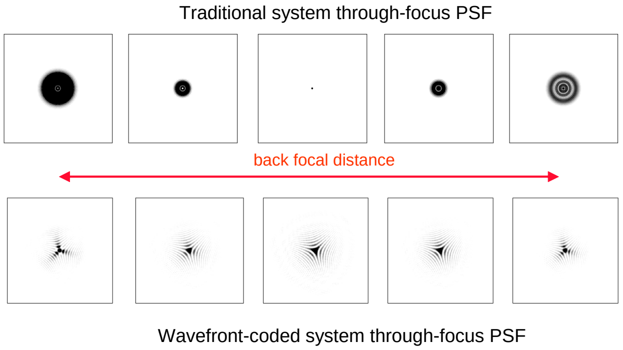

Fig. 2. The top row shows the point spread function (PSF) of a traditional system as a sensor moves through the image focal plane. At the point of best focus, the traditional PSF is very small, thereby producing high contrast images but as the sensor moves out of the focal plane the PSF grows corrupting the image in an uncorrectable fashion. The bottom row shows PSF for a wavefront-coded system. While the PSFs are larger than the best-focussed traditional system, they are both relatively invariant to defocus and correctable with image processing.

B. *Spectrally variant PSFs*

Another example of non-traditional optical properties is that of spectrally variant point-spread functions. Traditional optical systems attempt to minimize the variation in the optical PSF as a function of wavelength. Recent work demonstrates that by allowing or even enhancing the spectral (chromatic) variation in the optical PSF can enable new form factors as well as enhance the depth-of-field [11], [12]. In both works, the depth information of the object z_o is encoded into the spectrum by way of chromatic aberration (spectral-coding). In other words, the different color channels of the Bayer pattern will be in focus depending on the depth of the object. Figure 3 shows example images of a grayscale Air Force test chart at two different depths for an RBG spectral coded optical system. The set of images show the red channel having sharp focus when the target is located at 1.5 meters while the blue channel is out of focus. Conversely, when the target is at 0.13 meters, the red channel image is out of focus and the blue image is in focus.

The image processing for such systems must first identify the object depth by way of the relative sharpness between the color channels and then subsequently sharpen the entire image based on a model of the color and depth-specific PSF. Such an approach is quite different from the traditional approach to image processing which first demosaics the Bayer pattern and then sharpens the digital image in the luminance space. Fusing the different color channel images into a single high-quality image will require novel applications of spectral correlations

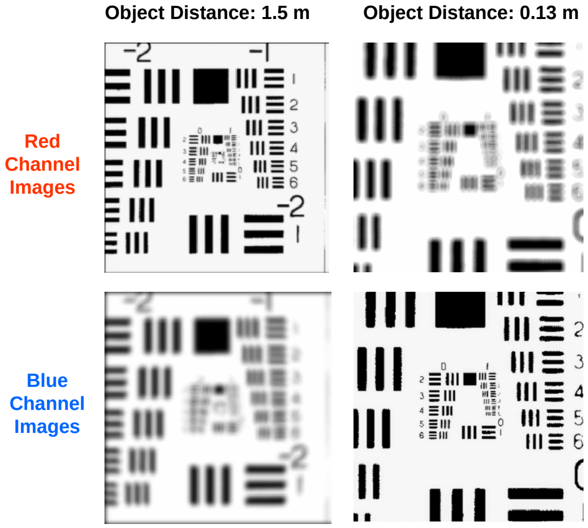

Fig. 3. The top row shows the images of a test chart at 1.5 meters (left) and 0.13 meters (right) from the red channel of a spectrally-coded system. The bottom row shows the images of a test chart at 1.5 meters (left) and 0.13 meters (right) from the red channel of a spectrally-coded system. Unlike traditional optical systems, the depth-dependent PSF varies considerably between the different color channels as evidenced by the blurriness of the red channel image at object distance of 0.13 meters and the blurriness of the blue channel image at 1.5 meters.

in imaging. In addition, special contrast or edge filters based on the spatial layout of the color filter arrays may improve the accuracy of both the object depth estimation and color image reconstruction.

C. Spatially variant PSFs

A final example of the unique properties of non-traditional optical systems is the spatial variability of the PSF. In traditional optical systems, the optical subsystem is optimized so that the PSF is basically spatially-invariant. This obviates the need for complex spatially-varying image processing. Recent research shows that optimizing a digital-optical system from an end-to-end perspective can enable high quality imaging with low optical subsystem cost by balancing minimizing digitally uncorrectable optical aberrations at the expense of those which may be subsequently corrected [1]. For example, the optical aberration coma is information-preserving, meaning that it can be corrected via subsequent digital post-processing. The processing, however, must operate in a spatially varying fashion. Figure 4 shows an example of the PSF as it varies according to the radial distance from the optical center of the image.

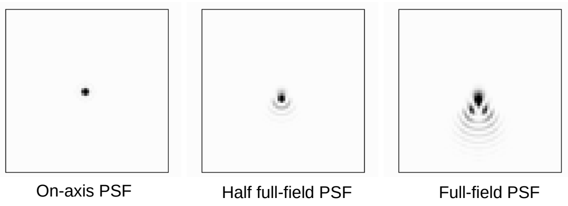

Fig. 4. The figure shows the spatial variation in the PSF as a function of field angle for the optical aberration of coma. Coma is one particular aberration which can be corrected with image processing, but the space-variant nature of the PSF requires space-variant digital filters.

The most common form of image processing and specifically sharpening involves application of a spatially invariant sharpening filter. Correcting a spatially varying PSF requires more complex image processing. Recently, researchers have begun developing spatially varying image processing while paying specific consideration to the optical properties of a system [13]. This implementation is based on matrix operations making it very impractical for real-time hardware implementations. Practical application of spatially varying image processing will require novel and efficient hardware location computation to compute the proper processing *on-the-fly*. Such work will take advantage of the polar symmetry common to optical imagery.

IV. CONCLUSION

In conclusion, we believe that the field of joint digital-optical imaging systems offers several challenging problems to the image processing community. The characteristics of these non-traditional optical system requires novel image processing algorithms, quality metrics, and real-time implementations to bring these exciting new imaging systems from the lab into the marketplace.

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