Image restoration in fiber-coupled imagers using space-variant impulse response characterization

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Received 18 October 2016; revised 28 March 2017; accepted 7 April 2017; posted 10 April 2017 (Doc. ID 278997); published 4 May 2017

Fiber-coupled image sensors have attracted interest in recent years for high-resolution conformal image transfer, including mapping of the spherical image surface of a monocentric wide-angle lens to one or more flat focal plane sensors. However, image resolution is lost due to fiber bundle defects, moiré from lateral fiber-sensor misalignment, and blur due to the nonzero gap between fiber bundle and the image sensor. Here we investigate whether subpixel impulse response characterization of the strongly shift-variant impulse response can be used with existing image-processing techniques to recover the resolution otherwise lost in image transfer. We show that the sub-micrometer impulse response is experimentally repeatable, and can be used to recover image data and reveal fine features of the input surface structure of a 2.5 μm pitch fiber bundle.

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OCIS codes: (110.0110) Imaging systems; (110.2350) Fiber optics imaging; (110.1758) Computational imaging; (100.2000) Digital image processing; (100.3020) Image reconstruction-restoration.

https://doi.org/10.1364/AO.56.004003

1. INTRODUCTION

Some optical systems require a nonplanar image sensor, which is incompatible with the high-performance (large pixel count, low noise and sensitivity) focal planes fabricated with conventional complementary metal-oxide-semiconductor (CMOS) processing. One example is the curved image surface formed by a wide-field “monocentric” lens [1], which requires a far deeper curvature than can be achieved by elastic deformation of a continuous CMOS focal plane die [2], and requires more spatial resolution than can be achieved with a spatially segmented CMOS sensor structure [3]. However, optical fiber bundles (a dense array of small, high-index contrast multimode fiber cores with low-index contrast cladding) can transfer the image from the curved focal plane to the flat image sensor plane [1,4]. A fiber-coupled (FC) image sensor consists of a quasi-periodic fiber bundle (created by glass stretching, stacking, and restretching) bonded directly to the face of a perfectly periodic image sensor. The fiber pitch is typically around 2.5 μm, and with appropriate design may be reduced to 2 μm or less [5,6]. The input field of view in a FC monocentric lens imager achievable with a spherical-planar fiber bundle can be increased from approximately 50° with a single straight fiber bundle, to over 124° with a single tapered fiber bundle, where the fibers are curved towards the spherical input surface [7]. However, the high spatial resolution of the fiber bundles can be significantly reduced due to light transmission across any gap between the planar surface of the fiber bundle and the image sensor. This gap is typically several micrometers, which is comparable to the fiber pitch. Fiber defects and micrometer-size particles also appear as artifacts in the captured raw image. In addition, the variation in alignment between the image sensor and fiber bundle with different pitches introduces a moiré pattern to the sensor response, independent of the captured scene. The moiré pattern can be partially compensated through flat-field calibration [8], but the lost resolution due to fiber-sensor gap and misalignment is not reversible with simple image calibration.

Various methods have been used to restore the image that was distorted by a stationary scattering medium. Turbid lens imaging, for example, uses the transmission matrix of the scattering medium and wavefront shaping by exploiting spatial light modulators as well as angular spectrum decomposition to restore the image to the resolution limited by the numerical aperture (NA) of the imaging system [9]. This method and other similar methods [10–12] require a relatively complex characterization setup, and the illuminating light source is primarily limited to a coherent one. Some methods require interferometric detection of the scattered image [9–11,13–15]. Incoherent light source and wavefront shaping [16] have also been used to restore the image off the scattering medium, but a spatial light modulator has to be used to reshape the scattering medium’s wavefront.

The impulse response of a FC image sensor is strongly space variant due to irregularity and the modal effect of individual fibers, and due to the irregular relative position between the individual fiber cores and the individual pixels of the image sensor. However, the impulse response should be constant.
Therefore, a sufficiently precise 2D raster scan of the point spread function (PSF) with incoherent illumination may provide the information needed to recover the lost resolution from the blurred lower resolution detected image. The advantages of this method are that it is not limited to monochromatic or coherent light; no wavefront shaping device is needed to characterize the imager or reconstruct the blurred image, and once the FC imager response is known, it can be used to recover the lost information up to the fiber bundle pitch without adding complex elements to the system.

Because the system is not linear shift invariant (LSI), the use of shift-variant image restoration methods is essential. The signal-to-noise ratio (SNR) and the accuracy and repeatability of the PSF characterization are the limiting factors for faithful reconstruction of the image captured by a FC imager [17]. If the SNR of the imager is low, then both the input image and the characterized PSF are noisy, leading to inaccuracy in the image reconstructed by solving the inverse problem. If the PSF response changes, the characterization data are not accurate, further degrading the reconstructed image. In this paper, we characterize a FC image sensor, where light is transferred by a high spatial resolution (2.5 μm pitch) imaging fiber bundle to an attached (1.12 μm pitch) CMOS focal plane, and demonstrate reconstruction of the input image limited by the fiber bundle pitch.

The paper is organized as follows. Section 2 describes the characterization of the FC image sensor, investigating SNR and repeatability of the highly shift-variant impulse response, and characterizing the response of a subpixel raster scan over a small region of interest of the sensor. We then consider the strongly shift-variant PSF data and show that LSI reconstruction methods such as deconvolution cannot be applied for image restoration. In Section 3, we apply and compare several established linear and nonlinear shift-variant image reconstruction techniques on the sensed image data, showing that the processed image appears to reveal features of the fiber bundle not visible in the raw images. In Section 4, looking at images processed by the iterative expectation maximization (EM) method, we confirm that the revealed fiber structure corresponds to the input fiber bundle itself, shown by microscopic inspection of the corresponding area at the input facet of the FC sensor. Section 5 provides conclusions.

2. FC IMAGE SENSORS

Imaging fiber bundles impose limitations on image transfer, including resolution limits and a shift-variant impulse response. This section discusses the properties of FC image sensors. We first address factors affecting the spatial resolution and SNR of FC sensors, including the fiber bundle and coupling to the image sensor. Next, we present a subpixel experimental characterization of the PSF in a FC sensor, and introduce a quantitative metric to assess the repeatability of these measurements.

A. Spatial Resolution Limit, Detection Mechanism, and Noise

The resolution of imaging fiber bundles is limited by the refractive index contrast between the core and cladding of the fiber. As an example, refractive indices of 1.81 and 1.48 are achieved for the core and cladding, respectively, with high-performance (NA 1.0) 24AS fiber faceplate material provided by Schott Fiber Optics [18]. This limits the fiber bundle pitch to 2.5 μm for 70% fiber core fill factor (the ratio between the core area to the total area of the fiber bundle), where the cross talk between fibers is still negligible. The fill factor can be further reduced to increase the fiber resolution while maintaining negligible cross talk [5]. State-of-the-art image sensors used in compact cameras have pixel pitches as low as 1 μm. Figure 1(a) shows the Omnivision’s 13351 monochrome image sensor, which has a 1.12 μm pixel. Attaching a 2.5 μm pitch fiber bundle to the 1.12 μm pitch image sensor [Fig. 1(b)] limits the overall resolution of the imager to 2.5 μm. The schematic of the fiber bundle cross section is shown in Fig. 1(c), where the sensor grid (black rectangles) oversamples the straight fiber bundle (blue rectangles). The blue highlights represent fiber core area in the fiber bundle with 70% fill factor.

Figure 1(d) shows an example of the impulse response in a 12 pixel × 12 pixel region of the bare monochrome image sensor in Fig. 1(a), without fiber bundle or Bayer color filters. The impulse response was captured by placing a 25 μm pinhole in contact with the white LED light source at a long distance (2 m) away from the image sensor. Absorptive color filters were used to narrow this light spectrum. A 50× microscope objective with NA of 0.55 was used to focus the light down to a pixel. While most of the energy is confined within one pixel
of the image sensor, some background energy is detected in the adjacent pixels. This occurs due to the tail of energy in the Airy pattern of the optical probe that is created at the focus of the diffraction-limited microscope objective. The diameter of the diffraction-limited spot size near the center of visible range at a wavelength of 550 nm is 1.22 μm, slightly larger than the sensor’s 1.12 μm pitch.

Figures 1(e) and 1(f) show two representative samples of the PSF from the FC image sensor [Fig. 1(b)]. The best achievable PSF [Fig. 1(e)] is limited by the 2.5 μm fiber bundle and adhesive gap, which, as observed, yields a PSF restricted to an area of approximately 2 × 2 sensor pixels. When the illuminating point is positioned on the center of fiber, most of the energy is confined within the 2.1 μm width of the fiber core, which is close to twice the image sensor pitch (2.24 μm). Therefore, we expect the FC imager’s PSF to be confined within a 2 pixel × 2 pixel-wide region at its best, consistent with observation. The PSF shape is highly shift-variant and nonuniform within this area due to the irregularity in fiber core shape, misalignment between fiber and the 2 pixel × 2 pixel-wide area and the modal effect of light transmission thought the fiber bundle. In the case where the input PSF lands on the fiber cladding or absorber material (used in the fiber bundle for elimination of background light), light is spread into more than one fiber and the detected PSF might spread wider than the 2 pixel × 2 pixel limit [Fig. 1(f)]. This strong variation of PSF along with the micrometer-size gap between the backside of the fiber bundle and the image sensor are the limiting factors of the resolution in FC imagers. In this case, shift-invariant image restoration methods such as deconvolution may not be applied to recover the lost data. However, if the shift-variant PSF map is known as a function of input location, then one can use shift-variant image restoration methods to recover the lost resolution.

The schematics of the FC image sensor cross section along the fiber bundle length is shown in Fig. 1(g). The incident beam is focused on the surface of the fiber bundle on plane A. The resolution at this plane is limited by the performance of the system lens and it is considered to be linear shift-invariant, at least for a small field of view. The light is then coupled to the fiber bundle at plane B. The efficiency of coupling is determined by the location and angular spectrum of the incident beam, the surface roughness of the fiber bundle, and the number of modes supported by each fiber. A multimode fiber with a sufficiently large number of modes provides a more accurate sample of the incident beam. The coupled light then propagates to plane C. If the cross talk between fibers is low and the variation of fibers along the propagation direction is small, the propagation has little effect on the shape and intensity of the signal. The use of absorbing material in fiber bundle structure for cross talk suppression usually leads to uniform attenuation of the signal [5]. The light emitted from the planar surface of the fiber bundle is transmitted into the epoxy layer at plane D. Note that while it is possible in principle to bond the fiber bundle directly to the surface of a CMOS sensor die, a few micrometer-thick layer of UV-cured adhesive accommodates the differential thermal expansion of the glass and silicon. In cross sections of such bonded FC sensors, we have achieved adhesive thicknesses ranging from 1.8 μm to 5 μm. The thicker the epoxy layer, the more blur in the image detected by the image sensor at plane E. The blur can be increased by misalignment between the center of the fiber core and the center of the pixel’s active photodiode area. Therefore, the detected image at plane E is also not shift-invariant compared with the incident image at plane A.

The SNR of the overall imager and the repeatability of the PSF characterization determine the extent to which the lost data can be restored. Second-order parameters such as sensor nonlinearity would also limit the accuracy of the restoration process, but these effects are typically weaker and are not addressed here. An additional underlying assumption here is that PSF does not change over time either due to random mechanical stress or with environmental parameters such as temperature. For operation over a range of temperatures, there will be thermal expansion, and the PSF will require characterization at several temperatures, to allow generation of an interpolated PSF for the specific (measured) operating temperature, as was done for moiré compensation in Ref. [8].

The SNR of the imager can be estimated by selecting a flat region in the captured image and using the following estimation [19]:

\[
\text{SNR} = 20 \log_{10} \left( \frac{\mu_I}{\sqrt{\frac{1}{N} \sum_{i=1}^{N} (I_i - \mu_I)^2}} \right) \tag{1}
\]

where \(I_i\) is the input image selected at a flat region, \(N\) is the number of samples (pixels), and \(\mu_I\) is the mean of \(N\) images, \(I_i\).

The SNR of the bare sensor, without fiber coupling, was estimated to be 35.3 dB at 10 ms integration time. The SNR of the FC imager would be much smaller if the raw image is used directly without any calibration. Because the fiber bundle is strongly shift-variant, the standard deviation of the flat field would be relatively large using Eq. (1). Instead, one can first calibrate the detected RAW image using the average of multiple flat fields to compensate for the imperfect fill factor of the fiber bundle (70% core area in our case) and then apply the above equation to estimate the SNR of the FC imager. Using this calibration method, the SNR of the FC imager was estimated to be 32.8 dB. The process of attaching the fiber bundle to the same image sensor thus reduces the SNR of the imager by 2.5 dB. A similar 2.4 dB decline of SNR was observed using a 1 ms exposure time. This SNR estimate is used later for image reconstruction.

**B. PSF Characterization of Highly Shift-variant FC Imagery**

Figure 2 shows the schematic of the PSF characterization setup. A 25 μm pinhole in contact with a white LED light source was used as the optical probe. An apochromatic microscope objective with NA of 0.55 was used to focus the optical impulse on the FC imager. Three broadband color filters were used to evaluate the effect of wavelength on the PSF and its repeatability. Hoya’s 25A, x1, and 80A filters were used for red, green, and blue colors, respectively. It was also experimentally verified that PSFs captured by coherent (laser) light sources are highly variable and also limit the image reconstruction to a single
wavelength. Incoherent light was used for the experimental results presented here. A 2.5 μm pitch and 2.5 mm long fiber bundle are attached to the bare monochrome image sensor without a color filter array. The FC image sensor is mounted on a computer-controlled Dali E-2100 piezo stage, which is used to capture the 2D PSF map on a limited area of the sensor. The position can be varied with 20 nm steps, well below the 2.5 μm fiber or 1.12 μm image sensor pitches, or the 0.8 μm thickness of the low-index cladding between fiber cores.

To verify the repeatability of the experiment, the optical probe was scanned horizontally, and the resulting PSF was recorded as a function of the input location. The piezo stage was moved by 0.4 μm steps over a 10 μm range, and one PSF was captured at each step. An average of 10 scans was taken to smooth out the random PSF variations (e.g., due to sensor noise). To avoid the piezo actuator hysteresis, one can either reset the piezo’s voltage to zero volts at the end of each X or Y scan, or use the position feedback to compensate for its inherent nonlinearity. Here we reset the voltage to 0 V and nonlinearly compensated the input voltage to linearize the position output. It is important to know the spacing between the sample points and convenient to have a constant spacing between them; otherwise, the correlation between each captured PSF and the input probe location would be unknown.

Figures 3(a) and 3(b) show the intensity value of two specific (grayed diagonal) pixels, along the scan line (color arrow) and off the scan line, respectively, for the light source with the blue color filter. Here five 1D scans are compared, each being the average of 10 horizontal scans. As one can see, the measured average pixel values are fairly repeatable for various pixel locations. Similar trends were observed using the green color filter data in Figs. 3(c) and 3(d). Although the probe’s 0.4 μm step size is lower than the sensor’s 1.12 μm pitch, the variation of pixel values is sensitive to submicrometer movements of the probe. This strong shift variance occurs because of light coupling to various modes of the fiber bundle, which carry different amounts of power as they propagate through the bundle. A higher degree of repeatability is observed for blue and green color filters compared with the red color filter [Figs. 3(e) and 3(f)]. Stronger variations of the pixel values along the scan line result from longer transmitted wavelengths of the red color filter, larger diffraction-limited spot size, and further extension of guided modes in the fiber bundle. The guided modes are more confined at shorter wavelengths and therefore are less sensitive to the exact location of the input probe, which is approximately 1–1.3 μm wide in diameter. Likewise, the PSF repeatability of the white light is affected by the upper wavelength range of the LED source and therefore limits the accuracy of the measurements.

The green color filter data are fairly repeatable and lie in the middle of the visible range. From this point on, we used this light source for both 2D PSF characterization of the imager, as well as capturing the resolution chart image for restoration. Similar results may be achieved with the blue color filter or any other light source that yields a repeatable PSF measurement. The repeatability curves in Figs. 3(a)–3(f) were measured by replacing the color filters and repeating the same line scan over the identical path. Therefore, the resulting curves may also be considered as the spectral response of the FC imager at a particular region of interest. The root mean square error (RMSE) of the repeatability curves was calculated to quantitatively characterize the stability of the measurements. Because the exact impulse response is unknown, the average of the measurements was considered as an approximation to the exact one in calculating the RMSE for the collected data in Figs. 3(a)–3(f). The RMSE can then be calculated from

$$\text{RMSE} = \sqrt{\frac{1}{M} \sum_{i} (I_i - \overline{I})^2} \quad (2)$$

where $I_i$ is the pixel value for each line scan at position $X_i$, and $\overline{I}$ is the average of pixel values at the same position. Five RMSE values are obtained from each of the figures, where they could be averaged to get a single quantitative metric for repeatability. The resulting normalized RMSE percentage is presented in

![Fig. 2. Schematic of the automated PSF characterization setup.](image-url)
Table 1. Average RMSE of Repeatability (%) for the Measurements in Figs. 3(a)–3(f)

<table>
<thead>
<tr>
<th>Color Filter</th>
<th>Center Pixel</th>
<th>Top-Right Pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>2.31 (a)</td>
<td>1.62 (b)</td>
</tr>
<tr>
<td>Green</td>
<td>1.47 (c)</td>
<td>1.17 (d)</td>
</tr>
<tr>
<td>Red</td>
<td>5.46 (e)</td>
<td>4.02 (f)</td>
</tr>
</tbody>
</table>

Table 1. This metric consistently indicates higher stability of the blue and green color filter data.

Having verified the repeatability of the measured data, the complete PSF data were captured as a function of input probe location. The shift-variant PSF map of the imager was captured as a function of input probe position by nonlinearly driving the piezo stage. Each line scan was followed by setting the piezo voltage to zero volts to avoid hysteresis. An area of 24 pixels × 24 pixels wide (26.88 × 26.88 μm²) was characterized using a step size of half the sensor pixel pitch (0.56 μm). The total number of PSFs is $47 \times 47 = 2209$. The submicrometer step size is useful, as the fiber bundle cladding and absorber have comparable widths and the captured PSF is thus sensitive to these half-pixel-pitch displacements.

Figures 4(a) and 4(b) show the variation of the peak intensity (single pixel) and the integrated power of the entire $47 \times 47$ PSF region as a function of input probe location, respectively. Both peak intensity and integrated power vary strongly with probe position. If the optical probe lands on the fiber core, the maximum intensity and power are transmitted. If the probe lands on the fiber cladding, light coupling is reduced and divided into multiple fiber cores. Finally, landing the optical probe on the absorber material minimizes both transmitted intensity and detected power. The relative position of fiber cores and sensor pixels also contributes to stronger shift variance of FC imagers.

In this case, the linear shift-invariant assumption is not even remotely accurate, so shift-invariant restoration methods such as deconvolution cannot be applied for image reconstruction purposes. However, one can lexicographically order each of the captured PSFs into a column vector and form a PSF matrix $H$ with each column representing one PSF and each row representing the position of the input probe. The detected blurred image $g$ can then be related to the original image $f$ through the following equation:

$$g = Hf.$$  \hspace{1cm} (3)

For simplicity, the detected 24 pixel × 24 pixel image was bilinearly interpolated to match the input probe’s $47 \times 47$ map. This way $H$ becomes a 2209 × 2209 square matrix, and $f$ and $g$ are both 2209 × 1 column vectors. Higher-order interpolation methods with better fidelity may also be used to obtain the high-resolution image. Cubic interpolation was used for image restoration for samples of the current data, with no significant improvement. This may be due to the limited SNR of the small pixel CMOS sensor. It will be important to consider higher-order interpolation for FC sensors with higher SNR. The characterized PSF matrix is shown in Fig. 5. For a
shift-invariant and sensor-limited imager, $H$ would become a diagonal matrix and Eq. (3) could be solved via deconvolution. However, in a FC imager, the individual fibers carry the input scene energy through multiple modes, which vary in shape and coupling coefficient. The modal effect of light transmission along with the imperfect fill factor of the fiber bundle (70%) results in the shift-variant PSF matrix $H$ that is not necessarily diagonal. In order to restore the lost resolution, one has to use shift-variant image restoration methods. Equation (3) and its solution have been well studied in the past [20–22]; however, for the sake of completeness, we will briefly review the restoration methods that could be successfully applied to the experimentally acquired data in this work. In the following section, we discuss several of these methods and compare the image reconstructed using linear and nonlinear restoration methods.

3. SHIFT-VARIANT IMAGE RESTORATION

The strong variation of the PSFs in FC imagers suggests that conventional shift-invariant image restoration methods are not applicable. In this section, we examine a few shift-variant image restoration methods. The formulations are discussed in the first part, and the reconstruction results are compared in the second part of this section.

A. Formulation

The PSF matrix $H$ in Eq. (3) is ill-conditioned, and typically has zero determinant. Therefore, direct inversion of this matrix or the pseudoinverse solution [23] is impractical, especially due to noise constraints. Instead one can solve the following nonnegative least squares problem [24]:

$$\arg\min_{\hat{f}} \{ ||H\hat{f} - g||_2^2 \},$$

(4)

where $\hat{f}$ is the estimated restored image by solving Eq. (4) and $|| \cdot ||_2$ signifies the $L_2$ or Euclidean norm. The least squares solution yields decent results for cases where the noise is insignificant. However, no prior information of the noise is used in the mathematical model given by Eq. (3), so in the presence of noise, the result of reconstruction becomes less accurate. To improve the reconstruction result, one may introduce the noise into the model

$$g = Hf + n,$$

(5)

where $n$ is the noise vector, and it is generally assumed to be additive Gaussian with zero mean. One way of solving Eq. (5) is to use the linear minimum mean square error (LMMSE) method to find the estimated solution by minimizing the error term $e = f - \hat{f}$. The LMMSE solution is then found by solving the following [25,26]:

$$\arg\min_{\hat{f}} E\{ e^T e \} = E\{ Tr(e^T e) \},$$

(6)

where $E\{ \cdot \}$ and $Tr$ denote the expected value operator and trace of a matrix, respectively. The solution requires knowledge of the autocorrelation matrix of the true image $f$, while in practice only the detected blurred image $g$ is known. Another shortcoming of the linear restoration methods is the presence of negative pixel values in the reconstructed image. One way to overcome this limitation of the linear methods is to solve them iteratively. Tikhonov regularization [27,28] is widely used to solve Eq. (3) by introducing a regularization parameter and calculating the Euclidian norm of the solution or solving

$$\arg\min_{\hat{f}} \{ ||H\hat{f} - g||_2^2 + \lambda^2 ||C\hat{f}||_2^2 \}. $$

(7)

Here $C$ and $\lambda$ are the regularization matrix and regularization parameter, respectively. Most common choices of $C$ are the simple identity matrix, a diagonal weighting matrix, or the first and second derivative operators [29]. Typical choices of the regularization parameter are the $L$-curve [30] and generalized cross-validation [31] methods. The identity regularization matrix and $L$-curve method are used in this work. The solution to the above equation can be found in the following closed form:

$$\hat{f} = (H^TH + \lambda^2 C^TC)^{-1}H^Tg.$$

(8)

To overcome the negative pixel values problem, one can nonlinearly solve the optimization problem given by Eq. (7) in an iterative fashion by calculating the residual error at each iteration step. Nonnegativity is achieved by imposing negative pixel values to be zero at each iteration step. This gives us the well-known iterative constrained Tikhonov–Miller (ICTM) restoration [28,32,33]. The minimum of the Tikhonov regularization functional in Eq. (7) is found by using the method of conjugate gradient [34]. The conjugate gradient direction $d^k$ at $k$th step is calculated from

$$d^k = r^k + \alpha^k d^{k-1},$$

(9)

where $r^k$ is the steepest descent direction given by

$$r^k = (H^TH + \lambda^2 C^TC)^{-1}H^Tg,$$

(10)

and $\alpha^k = ||r^k||_2^2/||r^{k-1}||_2^2$. The subsequent iteration is obtained by calculating the following nonnegative projection, where the negative image values are clipped to zero:

$$\hat{f}^{k+1} = \max(0, \hat{f}^k + \beta^k d^k).$$

(11)

Without the nonnegativity condition, $\hat{f}^{k+1}$ minimizes the Tikhonov functional in Eq. (7). Here the coefficient $\beta^k$ is the optimal step size, and its proper choice improves the convergence speed. Various methods can be used to find the optimal step size. Some examples are the standard step size of the conjugate-gradient method without the nonnegative projection, the golden selection rule, or first-order Taylor expansion of Eq. (11) with respect to $\beta^k$ [34,35]. Here we used the conjugate-gradient method step size for constrained adaptive restoration. The explicit expression for optimal $\beta^k$ is given by [33,36]

$$\beta^k = \frac{(r^k)^T d^k}{||Hd^k||_2^2 + \lambda^2 ||Cd^k||_2^2}. $$

(12)

The ICTM restoration yields a converging nonnegative result at the expense of more numerical complexity and lower computational efficiency. The iteration can stop when a threshold of relative error is reached. We used 1% relative error in this work, where it is defined as

$$\text{Err} = \frac{||f^{k+1} - f^k||_2}{||f^k||_2}. $$

(13)
Instead of using the $L_2$ norm regularization factor, one can introduce prior knowledge of the input scene sparsity by modifying the regularization term in Eq. (7). Cao et al. [37] used the $L_1$ norm regularization to incorporate sparsity and solved the following optimization problem using EM [38,39]:

$$
\text{min} \{||Hf - g||^2 + \gamma ||f||_1\}. \tag{14}
$$

EM finds the maximum likelihood estimate of $f$ iteratively in two steps. In the first step, the expected value of $f$ is estimated (E-step) from the observed data and the current estimate of model parameters. In the second step (M-step), the likelihood function is maximized, assuming the missing data are known. The details of solution to Eq. (14) are presented in Refs. [37–39]. The nonnegative projection is used at each iteration step to impose nonnegativity. We will show that nonlinear restoration methods such as ICTM or nonnegative EM are sufficient to restore the image to fiber-limited resolution. Other image restoration methods such as Schulz blind deconvolution [40] or total variation-based regularization [41] may be used for deblurring the highly space-variant FC imager; however, a complete investigation of these methods is beyond the scope of this work. In the following section, we will compare the discussed methods for our image restoration application.

**B. Experimental Restoration Results for Various Methods**

The FC output image suffers from fiber artifacts as well as moiré pattern due to misalignment between the irregular fiber bundle and the image sensor with different pitches. Although flat-field calibration can partially compensate for fiber artifacts and the unavoidable moiré pattern, the lost resolution cannot be restored using this method. Figure 6(a) shows the detected RAW image by the FC imager in the 24 pixel × 24 pixel-region of characterization. The USAF resolution chart image was relayed through the microscope objective onto the FC sensor. As will be shown later, the fiber bundle is attached to the image sensor with a small tilt angle of ∼5° between the pseudoperiodic fiber array and the image sensor array, resulting in the apparent sampling of the captured image to be tilted as well. The bilinearly interpolated RAW image (47 pixels × 47 pixels) and the result of flat-field calibration are displayed in Figs. 6(b) and 6(c), respectively. Although the flat-field calibrated image is visually smoother, the lost resolution in the blurred image is not recovered.

Once the FC imager is characterized in the region of interest, this information can be used along with the discussed image restoration methods to recover the lost resolution. Figure 7 compares various image restoration methods for Fig. 6(a), starting from the worst. The trivial pseudoinverse restoration results in a completely distorted reconstructed image due to the large condition number (∼10^{19}) of the PSF matrix $H$; this reconstruction is not presented here. The least squares solution in Fig. 7(a) poorly reveals the vertical bars of the resolution chart due to low SNR of the imager and excluding the noise from image restoration calculations. We introduced a Gaussian noise with zero mean into the restoration model and solved Eq. (6) to get the LMMSE estimate of the image [Fig. 7(b)]. One problem with LMMSE is that prior knowledge of the true image’s covariance matrix is needed. Here the detected image $g$ was used instead. Another shortcoming with LMMSE and other linear restoration methods is the negative pixel values encountered after restoration.

To avoid the requirement for prior knowledge of the true image, one can use the well-known Tikhonov restoration, in which a regularization parameter is used to enable image restoration from the ill-conditioned PSF matrix. The result of Tikhonov restoration is shown in Fig. 7(c). The negative values were clipped to zero; however, further improvement may be achieved with the ICTM method [Fig. 7(d)], where the nonnegative image is restored iteratively. Alternatively, one can introduce sparsity as prior knowledge and use EM to restore the blurred image iteratively, as shown in Fig. 7(e). Both ICTM and EM produce nonnegative images that converge to 1% relative error defined by Eq. (13) within a few iterations. EM method is used for subsequent restoration of images.

**4. RESTORATION TO FIBER RESOLUTION**

A closer look at Figs. 7(c)–7(e) reveals what appears to be the fiber bundle structure, meaning that the image could be restored to that of fiber pitch resolution. Further improvement of the image resolution beyond the fiber pitch (close to the image sensor pitch) was not possible due to the low SNR of the imager and variations in the captured PSF.

![Fig. 6.](image)  
(a) Raw low-resolution image. (b) High-resolution image from bilinear interpolation of RAW image. (c) Flat-field calibrated image.
In a similar experiment, the USAF resolution chart was placed in contact with the FC image sensor. An index-matching oil with refractive index of 1.6 was used in between to minimize scattering and image blur due to an unwanted gap. The EM method was used to recover the lost resolution from the experimental PSF matrix $H$. Figure 8 shows the detected blurred RAW images on the top row and the result of iterative EM restoration on the bottom. Elements 5 and 6 of group 7 in the resolution chart were used to evaluate the performance of the FC imager and the experimental image reconstruction. Both input and restored images were gamma corrected with a coefficient of 1.4 for better visual appearance. A clear improvement in the resolution of the detected image is observed, and the fiber bundle structure is once again observable in all the restored images. The dark spots in the bottom right image reveal the cladding and absorber regions of the fiber bundle that are approximately the size of less than a micron.

To verify that the observed fiber structures are not artifacts of the restoration process, a hexagonal aperture was imaged onto the FC image sensor and a microscope image of the input facet of FC sensor was captured while it was closed down near the region of characterization [Fig. 9(a)]. One can observe the irregular array of fibers with yellow cores and dark cladding and absorber regions. The fiber core boundaries in the region of interest [the red square in Fig. 9(c)] were extracted from the microscope image by simple image processing [Figs. 9(e)]. This process consists of converting the captured image to black and white, and registering the transition between black region and white regions as core boundaries. The same image was simultaneously captured by the FC image sensor [Fig. 9(b)]. As one can see, individual fibers are not visible in the unprocessed RAW image; transmission through the adhesive gap between the output fiber bundle face and active sensing area has blurred the fiber structure. The captured image from the FC image sensor in the region of interest [Fig. 9(d)] was processed using the EM restoration. The processed image [Fig. 9(f)] clearly reveals details of the fiber bundle structure that are normally not detectable in the RAW image. Extracted core boundaries from the microscope image were then superimposed onto the processed image of the FC sensor [Fig. 9(g)]. The excellent match between the extracted core boundaries and the fiber structure from the restored image confirms that with proper characterization and image processing, the blurred image in the FC imager can be restored up to the fiber pitch.

5. CONCLUSIONS

FC imagers have strongly shift-variant impulse response due to the imperfect fill factor of the fiber bundle as well as the difference between the irregular fiber bundle pitch and the image sensor pitch. The misalignment between the fiber cores and individual pixels also contributes to the strong shift variance.
This strong shift variance, along with the inevitable spacing between the fiber bundle and the image sensor, introduces image blur and loss of resolution. We experimentally characterized a region of interest in the FC image sensor to restore this loss of resolution. The measured PSF map was obtained by 2D scanning of the FC imager with a diffraction-limited microscope objective. Various shift-variant image restoration methods were compared to retrieve the lost resolution. Using iterative and nonlinear image restoration methods such as ICTM and EM, we were able to recover the lost resolution up to the fiber pitch. We also verified that the extracted fiber core boundaries from the microscope image match the fiber bundle structure that was obtained by proper image processing. Prior knowledge or control of environmental parameters may affect the quality of image restoration in these types of imagers. Further resolution improvement may be achieved, provided the PSF characterization is accurately repeatable and the FC imager has sufficiently high SNR.

**Funding.** Defense Advanced Research Projects Agency (DARPA) (W911NF-11-C-0210).

**Acknowledgment.** We thank Dr. Mark A. Neifeld from the University of Arizona and Dr. Ilya Agurok from the Photonic Systems Integration lab at the University of California San Diego for their invaluable discussions and suggestions. The bare monochrome Omnivision image sensors, and interface electronics, were provided by Google ATAP.

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