# Computational imaging system that can see outside the sensor boundary

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***Abstract*—We propose a computational imaging system using the concept of multiple point impulse response (MPIR), that allows image capture from the area of the sensor beyond its physical boundary. The gain in space-bandwidth product of our optical imaging system is achieved without affecting the diffraction-limited resolution of the system.**

***Index Terms*—Computational Imaging, PSF engineering, Extended field of View, Random convolution, coded Aperture.**

## I. Introduction

Computational imaging deals with the optical system modification so that image information is recorded in a coded form followed by a reconstruction algorithm for decoding the raw information. It is typically observed that this approach combining optical hardware and algorithms enables imaging performance not possible with imaging hardware alone or image processing alone. One of the commonly encountered barrier is the trade off between the field of view (FOV) and the resolution in optical microscopes generally defines using the space-bandwidth product [1], [2]. The recorded FOV is further reduced by the digital sensors (CCD/CMOS) used to record the images digitally. The intuitive way to increase the FOV is to capture the large number of images by scanning across the desired FOV and stitch them computationally as it is used in panorama photography mode in digital camera as well as in digital pathology. However, this scanning and stitching process requires stable hardware implementations and sometimes leads to registrations artefacts.

The point spread function of a traditional imaging system is a single point impulse response (SPIR) and can be approximated as a delta impulse at the centre of image field. When the system PSF is SPIR in Fig. 1(a), there is essentially a pixel to pixel association between the object and the recorded image with some blurring effect arises due the diffraction limited spot size. As a result, the information existing outside the physical array sensor cannot be recorded. A novel approach of multiple point impulse response (MPIR) has been proposed by the authors [3] to extend the FOV in a single shot imaging configuration. In this work, wide FOV object information is multiplexed onto the small detector array using modified PSF termed as "MPIR" as shown in Fig.1(b). This will involve the recording of a visually unrecognizable image which then using an appropriate reconstruction algorithm leads to a system with an extended FOV beyond physical sensor boundary.

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## II. Extended FOV with MPIR

The problem of image recovery is formulated as a deconvolution problem with an "MPIR" PSF defined as the collection of delta impulses at the location $(x_i, y_i)$ as given by

$$p(x, y) = \sum_{i=1}^{N} w_i \delta(x - x_i, y - y_i), \tag{1}$$

where, $w_i$ is the weighting factor for the delta impulses and is equal to the normalizing constant and $N$ is the number of impulses in PSF. The distribution of delta impulses lies within the active area of the detector as illustrated in Fig.1(b). Data are generated by the convolution of the object function with the MPIR followed by the truncation of the scrambled image within detector window. Random Poisson noise with an average light level of $10^5$ photons/pixels was also added on the top of the data to simulate the realistic experimental situation. The MPIR PSF can be realised by placing an appropriate phase mask or computer generated hologram (CGH) corresponding to the PSF at the Fourier plane aperture of the standard 4F imaging system. The desirable phase mask or CGH can be readily generated by using the iterative phase retrieval algorithms [4]. This concept of extended FOV has similarities with the structured illumination imaging used to increase the Fourier extent of the imaging system, as described in [5]. The captured multiplexed information is then decoded by employing an optimization based algorithm to solve the inverse problem (pseudo-code available in [3]). The challenging part of the image reconstruction problem is that the recorded data is incomplete and also contains measurement noise. This leads to ill-posedness of the underlying problem and the solution cannot be obtained by any simplistic linear processing approach. In order to give rise to a practical robust image recovery, the typical reconstruction strategy will involve solution of an optimization problem of the form:

$$C(I_{in}) = ||S \odot [I_{out} - p * I_{in}]||^2 + \alpha TV(I_{in}) \tag{2}$$

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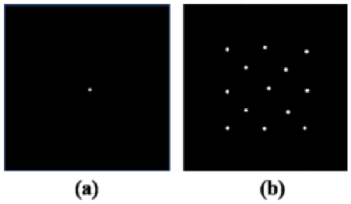


Fig. 1. Pictorial representation of PSF with impulse response approximated as delta impulse, (a) PSF of conventional imaging system as single point impulse response (SPIR) (b) PSF of unconventional imaging system as multiple point impulse response (MPIR)

where $C(I_{in})$ is the cost function we want to minimize in optimization problem. $I_{out}$ is the noisy data, $S$ is the operator representing truncation due to detector; and $I_{in}$ is the image we want to recover. $TV(I_{in})$ is the total variation penalty term for the regularization of the solution popular in imaging science literature as it encourages gradient sparsity.

## III. Simulation Result

A Siemens star shown in Fig.2(a) is taken as a binary object within a computational window of size $256 \times 256$ pixels. The active area of detector is defined within $128 \times 128$ pixels i.e. half of the size of the object as shown by yellow dotted square in Fig.2(a). The sensor size is such that, the outer region of the spokes object does not come inside the active region of the sensor as shown in Fig.2(b). Fig2.(c) is the captured multiplexed data with truncated sensor. The image reconstruction is performed using the sparsity based optimization algorithm described in [3]. The reconstructed image is shown in Fig.2(d) corresponding to the delta impulses in MPIR. However, in practical situations it is difficult to realise the delta impulse response due to finite size of Fourier plane aperture. Therefore, we also simulate the image reconstruction with Gaussian impulses in MPIR and the reconstructed image is shown in Fig.2(e). The FWHM of 2D- Gaussian function used in study is equal to the pixel width. As expected due to the extra blurring effect of Gaussian impulse function the image quality of reconstructed image is lower in Fig.2(e) as compared to the image reconstruction using delta impulse in Fig.2(d). The inaccessible information that initially lies outside the active region of the sensor is now reconstructed faithfully in both the cases without losing the diffraction limited resolution. The quality of images is quantified by using the relative mean square error (RMSE) and structural similarity index measure (SSIM) values between the ground truth and recovered images. Both cases uses the 1000 iterations of the algorithm explained in [3] The RMSE plot is shown in Fig.2(f). The solid line corresponds to RMSE with delta impulses and dotted one represent the RMSE with Gaussian impulses. After 1000 iterations the RMSE and SSIM values are $2.7 \times 10^{-3}, 0.99$ and $6.5 \times 10^{-2}, 0.97$ for the delta and Gaussian impulses respectively.

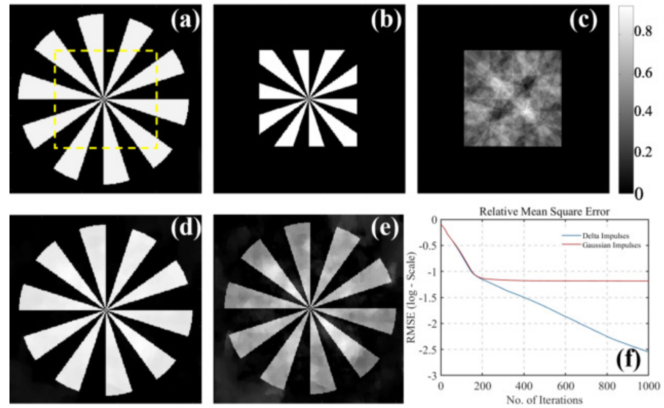


Fig. 2. (a) Ground truth image with yellow dotted square showing the active region of sensor within the half of the computational window. (b) Object information captured by the truncated sensor array. (c) Scrambled data with MPIR captured by the truncated sensor array. (d) Reconstructed object using delta impulses in MPIR. (e) Reconstructed object using the Gaussian impulses in MPIR. (f) The relative mean square error plot with respect to ground truth for the MPIR with delta and Gaussian impulses is shown by the solid blue line and red line respectively.

## IV. Conclusion

In conclusion, we have presented a MPIR concept to increase the space-bandwidth product of the computational imaging system. More specifically, we have shown that using MPIR as the PSF of the system it is possible to capture the information lying outside the active area of sensor array. This will increase the spatial extent of the captured image in single shot without losing diffraction limited resolution. The proposed extended FOV system concept is practically realizable and find multiple applications.

### *A. Abbreviations and Acronyms*

- MPIR - Multiple point impulse response
- SPIR - Single point impulse response
- PSF - Point spread function
- FWHM - Full width half maxima
- RMSE - Relative mean square error
- SSIM - Structural similarity index measure
- CCD - Charged Coupled Devices
- CMOS - Complementary metal–oxide–semiconductor
- FOV - Field of View

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