Platform motion blur image restoration system

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Abstract: We present a computational imaging system that incorporates an optical position sensing detector array, a conventional camera and a method to reconstruct images degraded by spatially variant platform motion blur.

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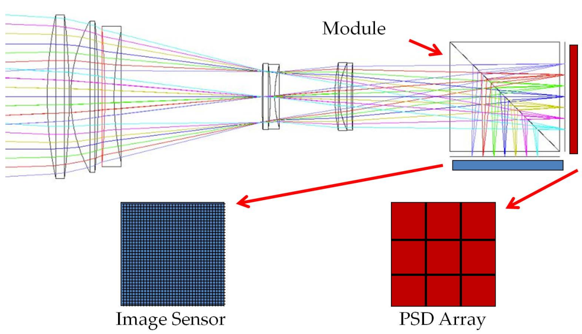
Image degradation caused by platform motion blur is a common problem for space based imagers. Platform motion blur is accentuated by long exposure times, large object distances, or rapid motion [1] and in many applications it is dominant over object motion blur. Platform motion blur varies across the image field in a structured fashion, characterized by translation and rotation; therefore, it can be modeled using an affine transform. Image deconvolution with a point spread function (PSF) estimate is used to deblur images degraded by spatially variant (SV) motion blur [2]. Limitations in this process can be reduced by measuring the PSF during image acquisition using additional hardware. A low spatial resolution, high temporal resolution video camera can be used to estimate a PSF [3], however, this increases size, weight, power and processing costs. One approach is to measure camera motion using accelerometers unfortunately the resolution of the measurements do not scale with the focal length of the lens [4]. The structured nature of platform motion blur makes it sufficient to detect motion from the image itself at a few locations in order to generate a SV PSF. We fabricated a prototype system capable of acquiring images while simultaneously tracking relative camera scene motion at specific image locations using position sensing detectors (PSD) and used it to form an SV PSF from which to significantly restore blurred images, Fig. 1.



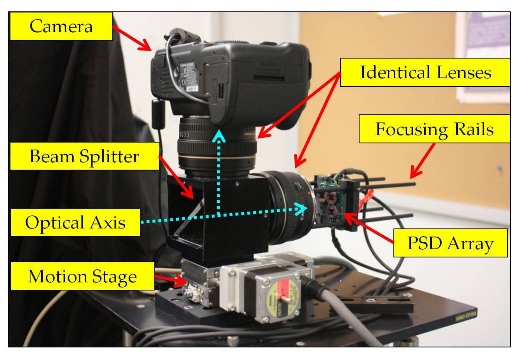


Fig. 1. (Left) Schematic: a lens and beamsplitter form identical image planes for the image sensor and PSD array. (Right) Photo of the imaging, position sensing & motion actuated system.

1. Measuring Image Motion using Position Sensing Detectors

The large energy collection area of the PSD allows it to provide fast analog position outputs. Light incident on the lateral effect PSD [5] generates a photo-current that flows across the uniformly resistive sensor surface and whose distribution is proportional to the centroid position of light intensity (X, Y) (1). The PSD also provides an output, S, which is proportional to the net intensity at the sensor. In these expressions, L refers to the distance between contacts and i_i are the currents at the electrodes, see Fig. 2a. We modeled lateral effect PSD behavior as scenes move across its surface in order to find how well it can measure the PSF. The simulation showed that localized features on a dark background are easily tracked with sub-pixel error. The plot in Fig. 2b shows that tracking is worse for images with low contrast features since they are less localized. The PSD motion estimate of the centroid is skewed toward the sensor's center as ambient light increases, Fig. 2c. Tracking is not possible if the feature moves off a sensor's surface. This event can be monitored using the PSD outputs. These simulations were confirmed experimentally by projecting videos onto the PSD. A PSD array is shown schematically in Fig. 2d, where valid and invalid tracking are denoted by green and red arrows, respectively. In order to recover invalid data, we propose forming PSD aggregate groups by joining adjacent PSDs in the array using (2). Here, the pairs $\{l, m\}$ and $\{o, p\}$ index the beginning and ending of the sensor group in the x and y directions, respectively. The subscripts u, v denote the index of the PSDs in the array. As opposed to the discrete PSDs available for the experimental demonstration, an aggregate group requires closely tiled PSDs to create a contiguous measurement space.

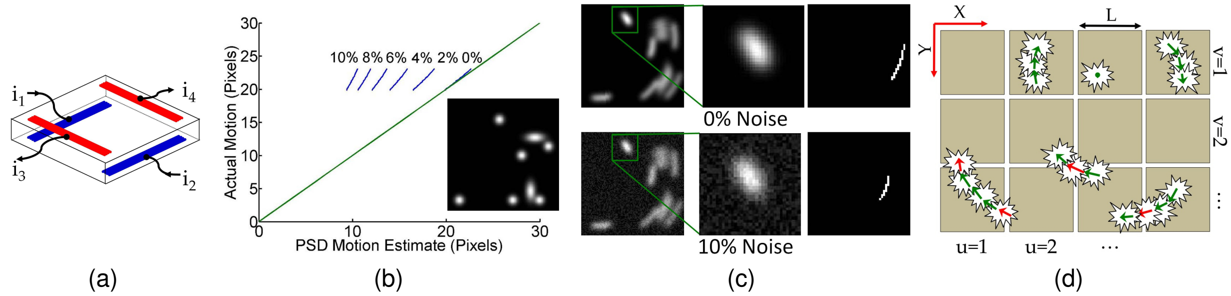


Fig. 2. (a) Lateral effect PSD schematic. (b) Plot of PSD scene tracking error for various noise levels. Input scene is inset. (c) Scene from Fig. 2b is blurred (left) and the centroid is tracked (right) with 0% and 10% noise present. (d) PSDs can track the moving centroid of high contrast features that remain on the sensors. Invalid data can be recovered by aggregating the outputs of a PSD array (2).

$$X_{u,v} = \frac{i_1 - i_2}{i_1 + i_2}\frac{L}{2} \qquad Y_{u,v} = \frac{i_3 - i_4}{i_3 + i_4}\frac{L}{2} \qquad S_{u,v} = i_1 + i_2 = i_3 + i_4. \tag{1}$$

$$X_{aggregate} = \frac{\sum_{u=l}^{m}\sum_{v=o}^{p}\left[\left[L(u-1) + X_{uv}\right] S_{uv}\right]}{\sum_{u=l}^{m}\sum_{v=o}^{p} S_{uv}} \qquad Y_{aggregate} = \frac{\sum_{u=l}^{m}\sum_{v=o}^{p}\left[\left[L(v-1) + Y_{uv}\right] S_{uv}\right]}{\sum_{u=l}^{m}\sum_{v=o}^{p} S_{uv}} \tag{2}$$

2. Generating a Spatially Variant PSF from PSD Data for Image Deblurring

We model image blur caused by platform motion by an affine transform, which is appropriate for many real scenes [6]. Coefficients of the transform $F = \langle a(t)x + b(t)y + c(t), d(t)x + e(t)y + f(t)\rangle$ for each elementary time step t are calculated based on consecutive voltage information produced by three PSDs placed in known locations of the image plane. Since each PSD provides a vector of elementary motion at its coordinates (x,y) we have unambiguous estimate of transform coefficients. Motion integration during the exposure time allows us to compute the PSF for any arbitrary image pixel location. A pixel by pixel deconvolution is performed using the Lucy-Richardson algorithm [7]. Each pixel value of the restored image is acquired by deconvolving in its square neighborhood and taking the central value.

3. Experimental Proof-of-Principle Result

The system shown in Fig. 1 is computer controlled to simultaneously trigger the motion stage, imaging camera and PSD data acquisition. The design requires the imager and PSDs be in the same image plane and prompted the fabrication of a custom cube assembly to house the beam splitter, imager and PSD array. A motion stage creates reproducible motion blur. We conducted experiments on the image in Fig. 3 producing SV blur evident in the scene. The scene contains three bright LED sources focused onto the region where the PSDs are located (shown in cyan). In this way we tailor the experiment to meet PSD requirements by providing localized, high contrast features to track. Overlaying the blurred images are yellow lines describing the calculated SV PSF showing the two are consistent. The system is limited to certain applications, such as for star imagers, where bright features of specific size and distribution appear on a dark background. The reconstructed image in Fig. 4 shows significant improvement and the system's effectiveness.

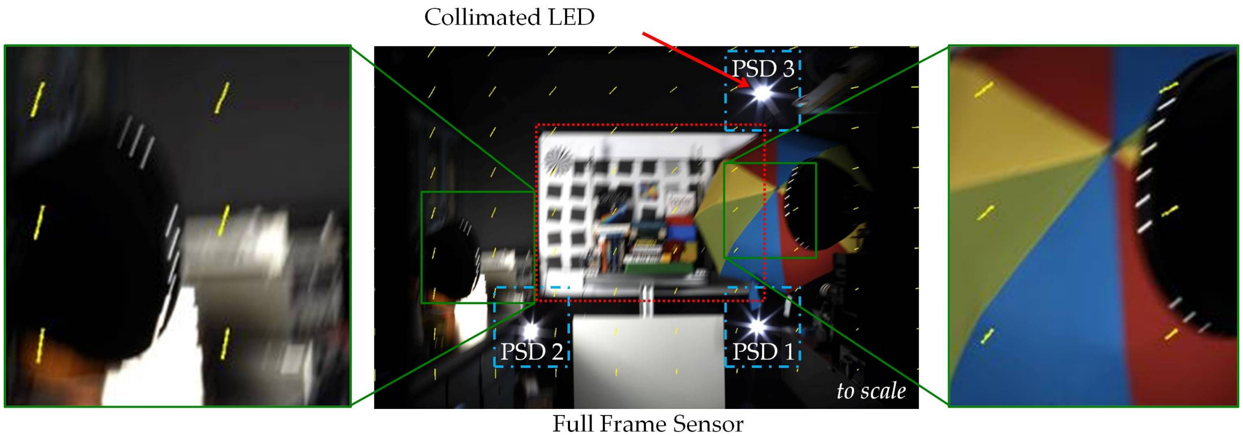


Fig. 3. Experimentally motion blurred image with magnified sections shown. The calculated SV PSF is shown superimposed as yellow lines and is consistent with the blur. PSDs are depicted in cyan.

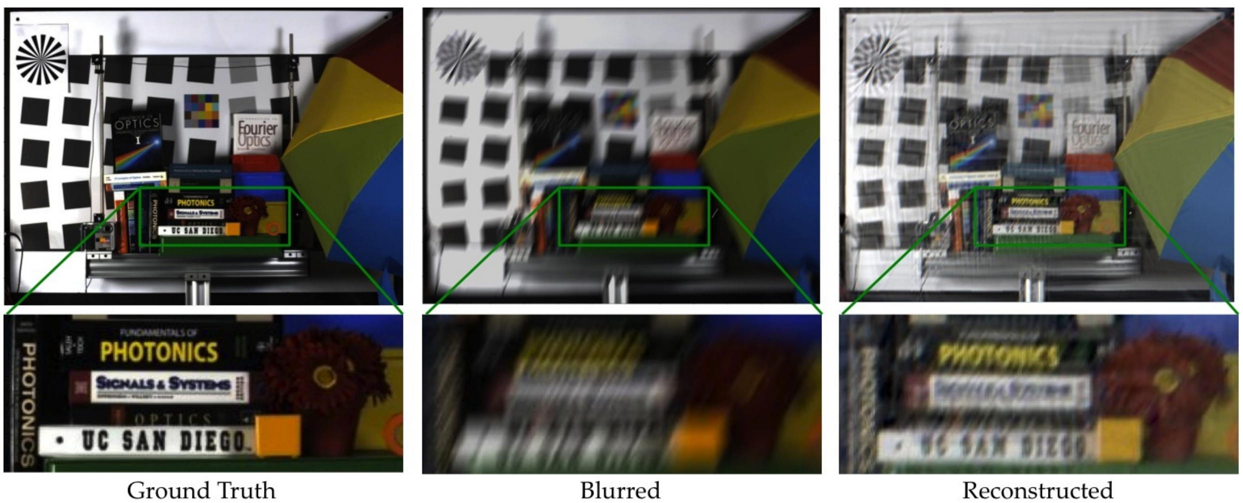


Fig. 4. The region of Fig. 3 enclosed in red is deblurred using a pixel by pixel method with the Lucy Richardson algorithm set to 15 iterations. Magnified sections of the images are shown.

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