Coded Exposure Photography: Motion Deblurring using Fluttered Shutter

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Ramesh Raskar, Amit Agrawal, and Jack Tumblin. Coded exposure photography: motion deblurring using fluttered shutter. In *SIGGRAPH '06: ACM SIGGRAPH 2006 Papers*, pages 795–804, New York, NY, USA, 2006. ACM

Darker scenes require longer exposure time, but that results in blurring of moving objects. Sensor sensitivity can be increased, but this unnecessarily penalizes the stationary background with noise. Conventional cameras open the shutter for the entire duration of the capture which is equivalent to applying a temporal box filter. This means that smeared moving objects lose high-frequency spatial details and recovery is an ill-posed problem.

The idea of the paper is to flutter the camera shutter open and closed rapidly using a pseudo-random sequence. This encodes high-frequency details in the motion blur itself and recovery becomes a well-posed problem even for large degrees of blur. The technique assumes constant radiance and opaque objects. Additionally, it reduces total exposure time by half. It also requires the user to select the blur path so that the point-spread function (PSF) can be estimated.

Let A be the smearing matrix, X the unblurred image and B the blurred image. Then we have $AX = B + \eta$, where η is measurement uncertainty. The authors use a least-square estimation to solve for the deblurred image: $\widehat{X} = A^{+}B$, where A^{+} is the pseudo-inverse of the smearing matrix A. The smearing matrix A can be calculated from the PSF and the on/off chop code (the flutter). The authors selected this code by maximizing the invertibility of the matrix A via standard matrix conditioning analysis. They minimize the condition number, which is the ratio of the largest to the smallest singular value. This reduces the sensitivity to noise in the blurred image. The number of chops was selected by experimentation to be 52 with 50% duty cycle. The near-optimal code found by a randomized linear search was 1010000111000001010000110011110111010111001001100111.

If a non-zero background is present, the blurred image is given by $B = AX + A_gX_g$, where X_g is the static background and A_g is a diagonal matrix which attenuates the background. If the object is blurred over a distance shorter than its length, then X and X_g can be uniquely estimated. Otherwise, every blurred pixel has a contribution from the background and there are no unique solutions.

The authors used a DSLR camera with a ferro-electric shutter placed over the lens. The shutter was controlled by a microcontroller triggered by the camera's hotshoe to send the code sequence during the exposure. The algorithm was then applied to synthetic and natural scenes. A photographic test pattern with various spatial frequencies was motion blurred and then deblurred. Traditional exposure resulted in loss of high frequencies. Coded exposure was successful at preserving them. Another experiment was a photograph of a moving taxi. The algorithm succeeded in revealing the text on the taxi. An interesting example involved a moving car occluded by a vertical pole. Since the pole was thinner than the maximum blur displacement, it was possible to remove it in the deblurred image by ignoring the occluded pixels.

The biggest weakness of the paper is that the PSF needs to be specified by the user. The available PSF estimation algorithms are not tailored to coded exposures. The authors say that coded exposure should make it easier, since higher frequencies are preserved in a single frame. However, they do not solve it in the paper. Additionally, their method to find a near-optimal code was not convincing. They searched the code by brute force in limited search space without finding a scheme behind a good code. This brute force approach also limits the possibilities for an adaptive variable length approach.

It would also have been useful to compare the results to photographs made by traditional exposure; or by video with a high frame rate combined into one frame via an optical flow-based algorithm. Video has a delay between frames as data is buffered out of the sensor array. This might give the coded exposure method an advantage, but it would have been nice to see if that's the case. The ferro-electric shutter blocks some light even when open, which adds to the effect of having the shutter closed 50% of the time (duty cycle of the code). The authors suggest sensor chip implementation of the coded shutter which solves the first problem, but it's not clear how the 50% trade-off fares against the high speed video camera approach mentioned above.

The paper does present a novel idea which could have applications in video surveillance under poor lighting conditions. The algorithm is simple and the technique will be more useful once PSF estimation is added.