A Framework for Analysis of Computational Imaging Systems With Practical Applications

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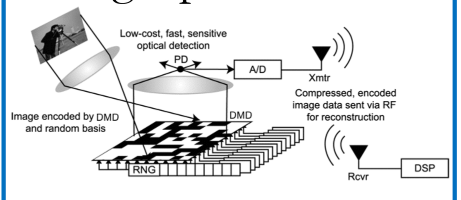
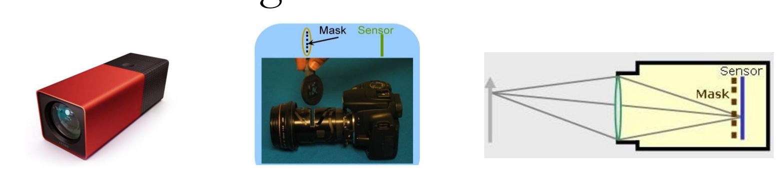
Our Goal: Analysis of Computational Imaging

Single pixel camera



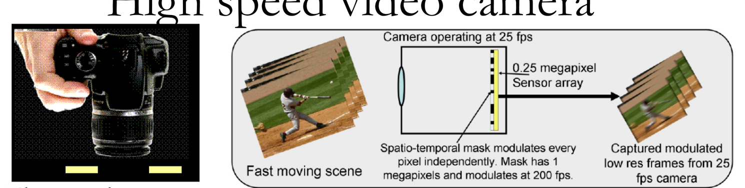
[Wakin et al., 2006]

Light field cameras



Lytro [Ng et al. 2007]; Coded aperture [Veera et al 2007, Levin et al. 2007]; Heterodyne camera [Veera et al., 2007]

High speed video camera



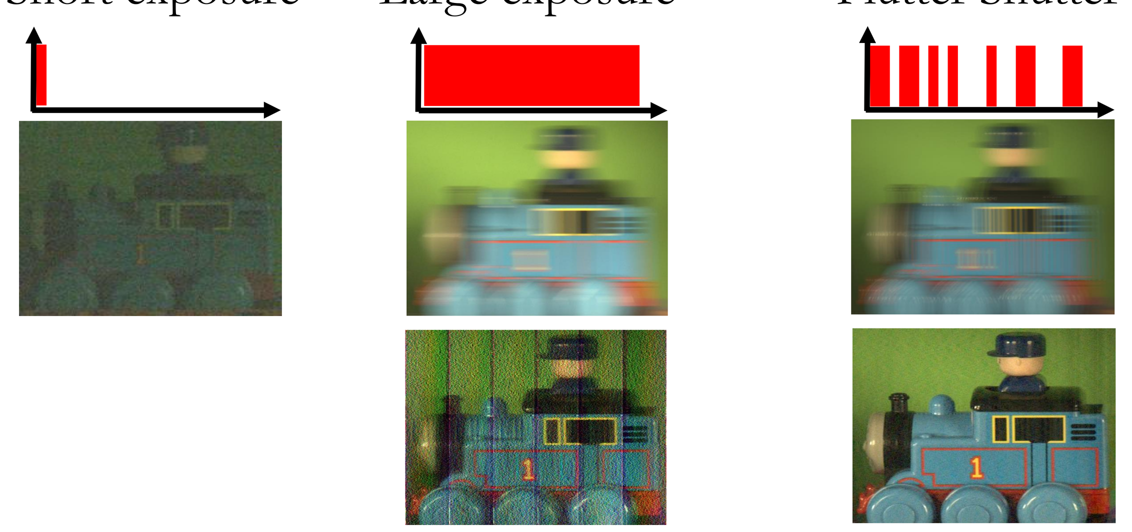
Flutter shutter [Raskar et al. 2006]; Programmable pixel compressive camera Reddy et al., 2011

- What is the expected performance?
- How does various design compare?
- How does lighting condition affect their performance?

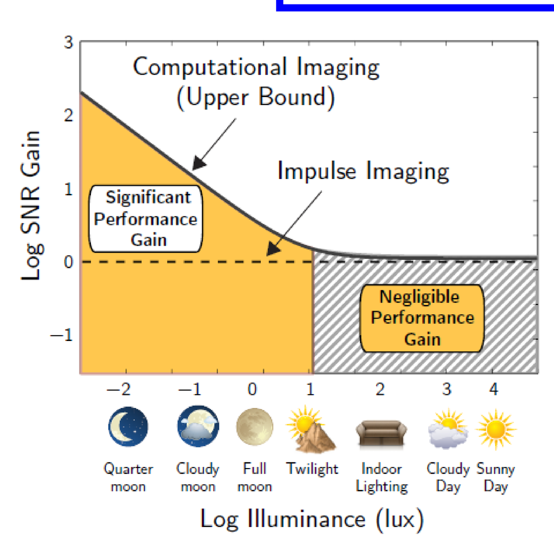
How does CI improve performance?

1) Increased light throughput 2) Well conditioned optical coding

Short exposure Large exposure Flutter Shutter



Prior work on analysis of CI systems



[Cossairt et al. 2012, Ihrke et al. 2010, Ratner et al. 2007]

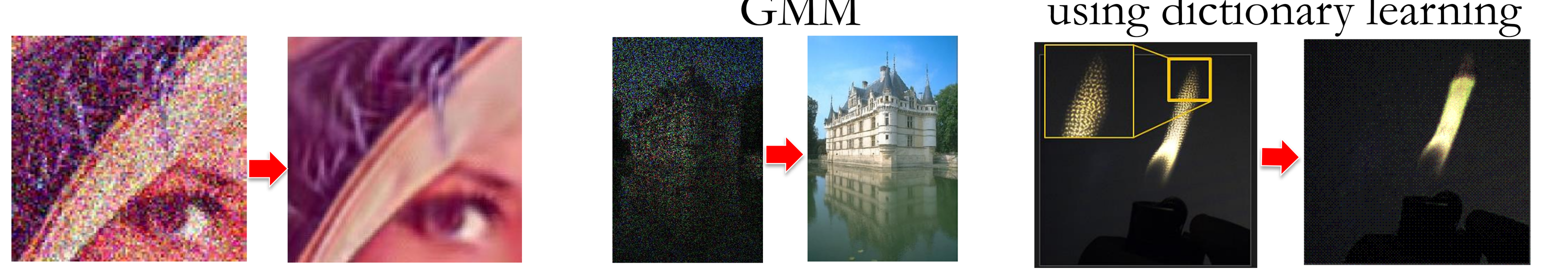
Related performance to practical considerations such as lighting levels and sensor characteristics

Large gain at low light levels

Limitation: Did not take signal priors into account

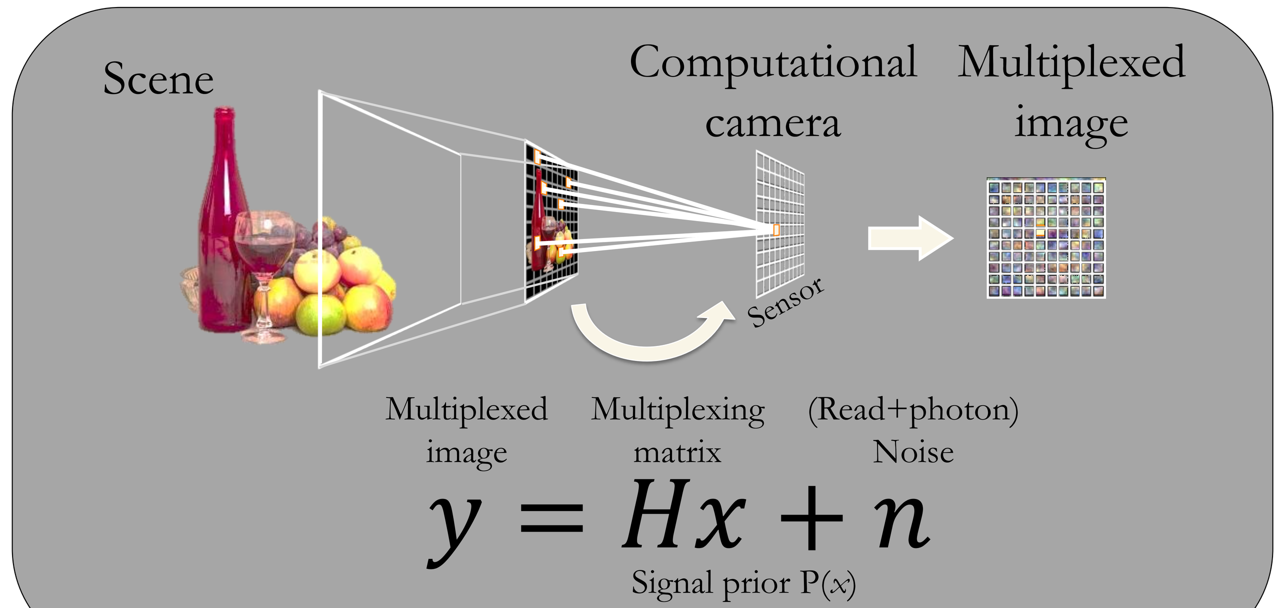
State-of-the-art algorithms use signal priors

Denoising using BM3D; Inpainting using GMM; Coded exposure video using dictionary learning



Dabov et al., 2011; Yu et al., 2011; Hitomi et al., 2011

Comprehensive analysis framework



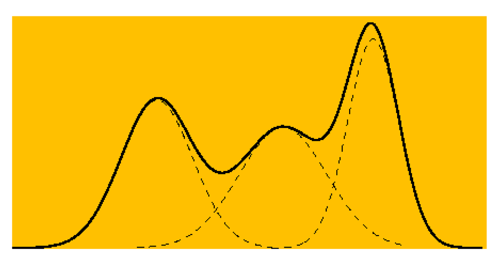
$$y = Hx + n$$

Our analysis takes into account:

- Signal prior
- Multiplexing matrix
- Noise characteristics

We model signal prior using Gaussian Mixture Model (GMM)

1.Universal approximation property

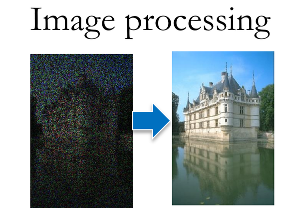


Sorenson et al., 1971

2. Analytically tractable
A special case is Gaussian prior, whose MMSE can be computed analytically

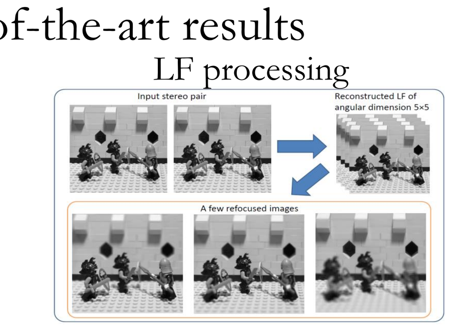
3. State-of-the-art results

Image processing



Yu et al. 2010

LF processing



Mitra et al. 2012

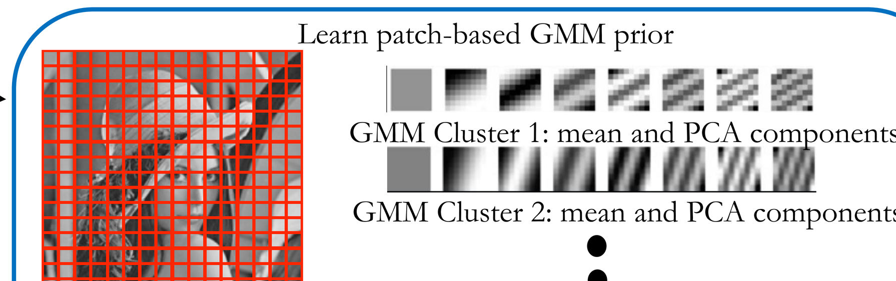
Complete specification of the analysis framework

Multiplexed image, Multiplexing matrix, (Read+photon) Noise

$$y = Hx + n$$

$$P(n) = N(0, (J + \sigma_r^2)I)$$

Learn patch-based GMM prior



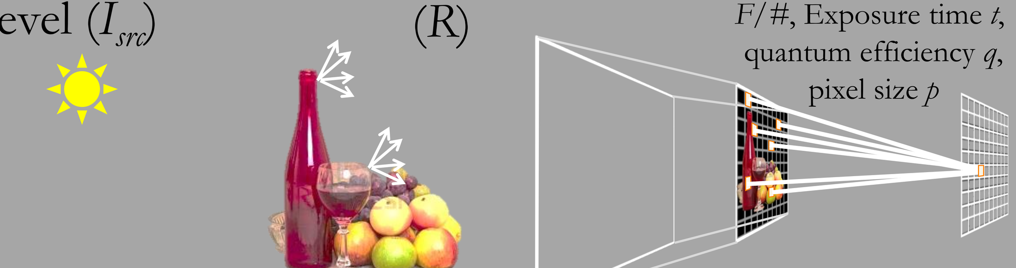
$$P(x) = \sum_{i=1}^{k} \alpha_i N(m_i, \Sigma_i)$$

Cluster weight; Cluster mean; Cluster covariance

We use the Minimum Mean Square Error (MMSE) as a metric to evaluate performance

Practical system performance depends on

1. Illumination level (I_{src}) 2. Scene reflectivity (R) 3. Camera parameters
$F/\#$, Exposure time t, quantum efficiency q, pixel size p



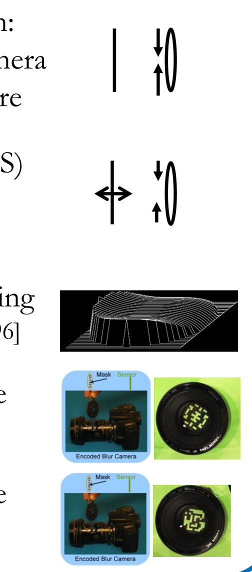
Average signal-level is given by:

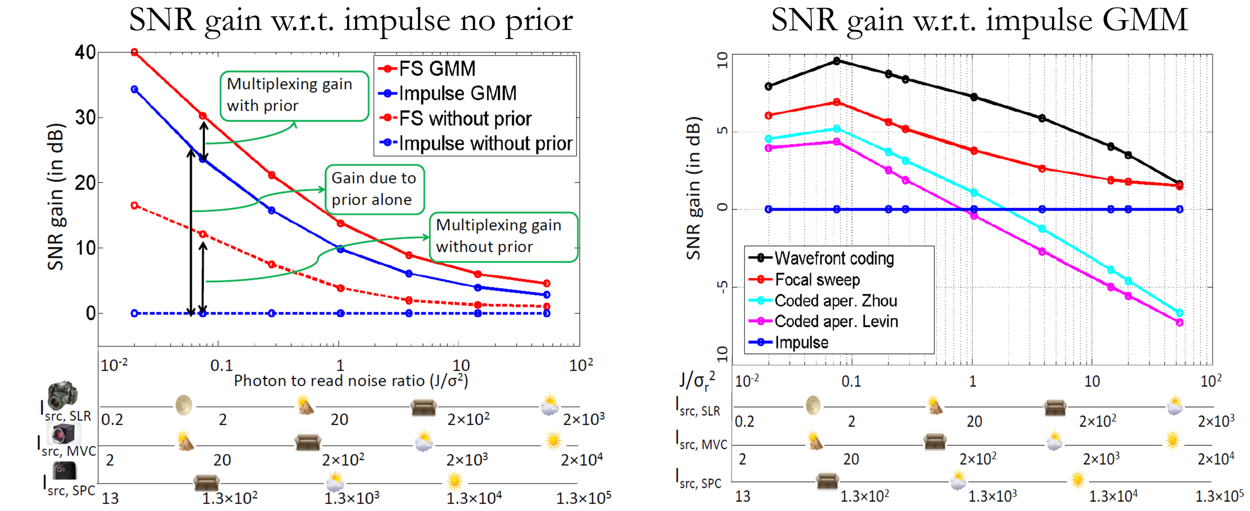
$$J \approx 10^{15} I_{src} R \left(\frac{F}{\#}\right)^{-2} tqp^2$$

Analysis of Extended Depth of Field (EDOF) systems

Systems compared:

1. Impulse system: Conventional camera with small aperture
2. Focal sweep (FS) [Hausler 72, Nagahara et al. 2008]
3. Wavefront coding [Dowsky, Cathey '96]
4. Coded aperture [Zhou et al. 2009]
5. Coded aperture [Levin et al. 2007]



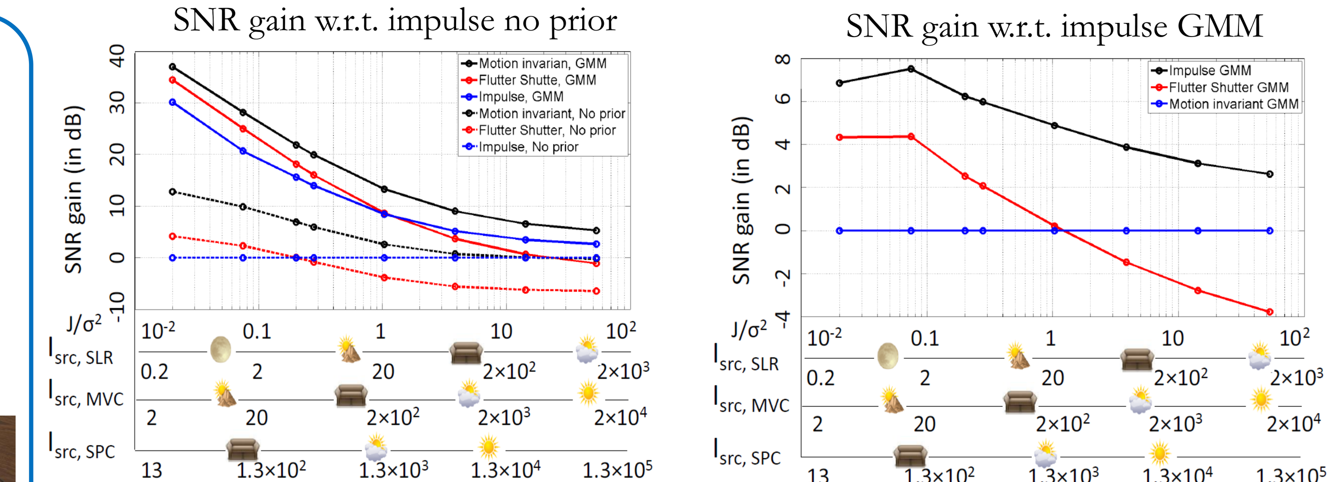


1. Signal prior improves performance of impulse and EDOF systems significantly
2. Wavefront coding performs 9.6 dB better than impulse system

Analysis of Motion Deblurring systems

Systems compared:

1. Impulse system: Conventional camera with small exposure
2. Flutter shutter (FS) [Raskar et al. 2006]
3. Motion invariant photography [Levin et al. 2008, Cho et al. 2010]

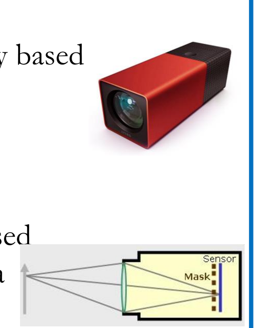


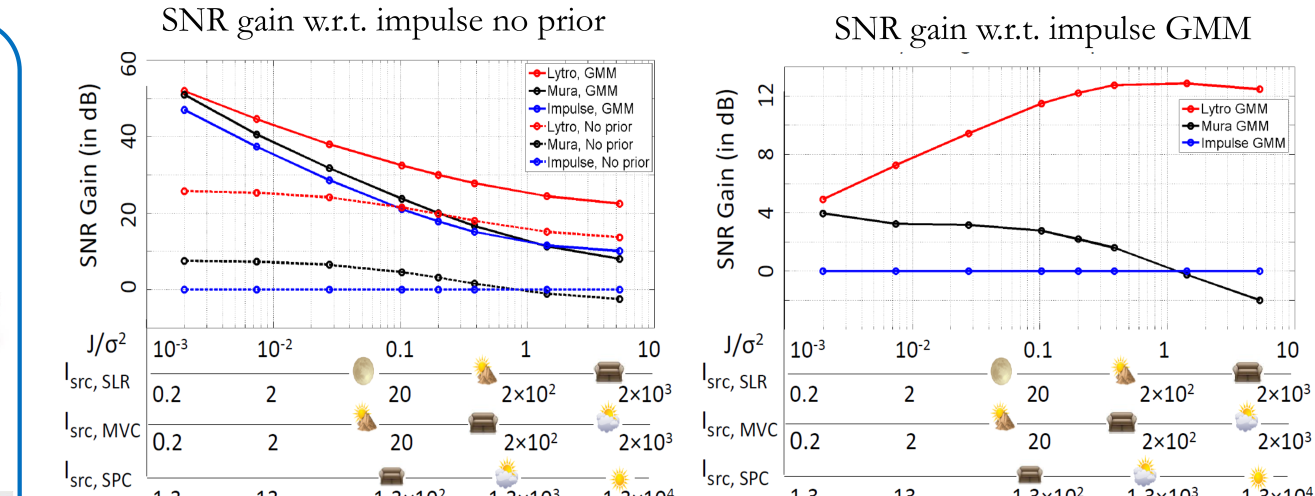
1. Signal prior improves performance of both impulse and motion deblurring systems significantly
2. Motion invariant imaging produces peak SNR gain of 7.5 dB

Analysis of Light Field systems

Systems compared:

1. Impulse system: Camera with pin hole mask placed near sensor
2. Microlenses array based Lytro camera [Ng et al. 2005]
3. MURA mask based light field camera [Lanman et al. 2008]





Lytro provides significant SNR gain at high light levels, but similar performance to MURA at low light levels

Conclusions

1. More gain due to prior than due to multiplexing
2. EDOF systems provide 9 dB gain over impulse imaging
3. Motion deblurring systems provide 7.5 dB gain over impulse imaging
4. Light field systems provide 12 dB gain over impulse imaging