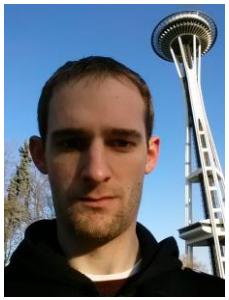
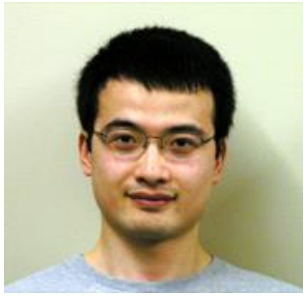
Random Coded Sampling for High-Speed HDR Video


Travis Portz, Li Zhang, and Hongrui Jiang

University of Wisconsin-Madison

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Motivation

Capture highest quality video possible from a sensor

- Push sensor to limits of its bandwidth and noise characteristics
- Full system approach: capturing and post-processing

Robustness to lighting conditions, motion

- Avoid saturation in bright regions, noise in dark regions
- Avoid blur for fast motions, maintain high quality for slow motions

Video deblurring difficult, prone to artifacts

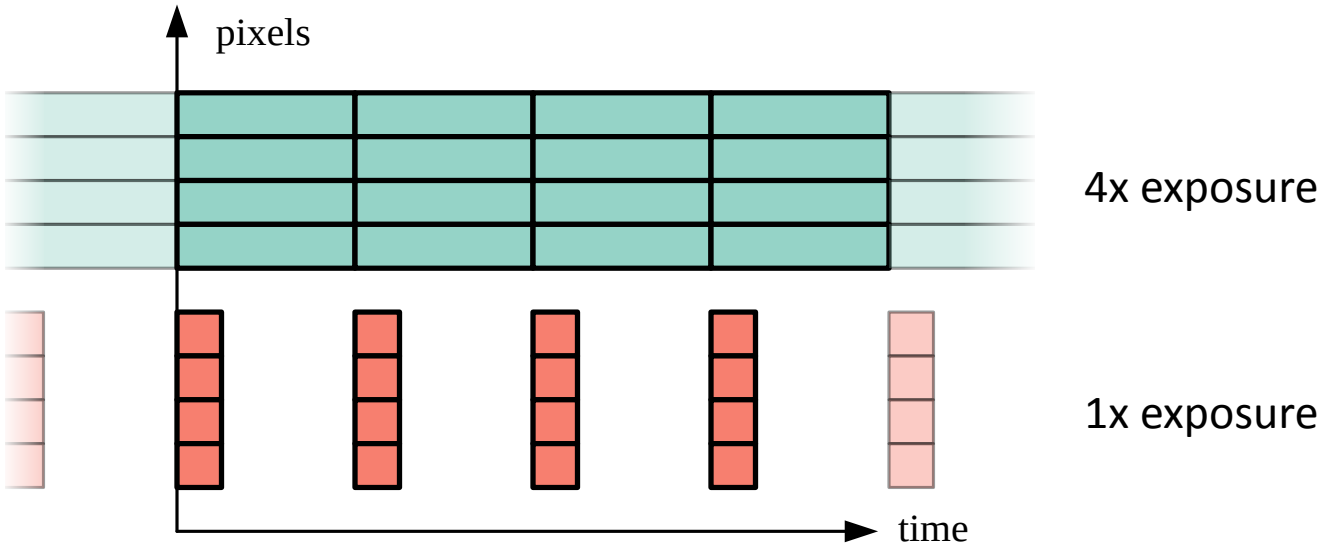
- Spatially-varying blur kernels

Existing methods can achieve higher frame rate or higher dynamic range, but not both simultaneously

Traditional Cameras

All pixels use the same exposure time

Full sensor readout every frame



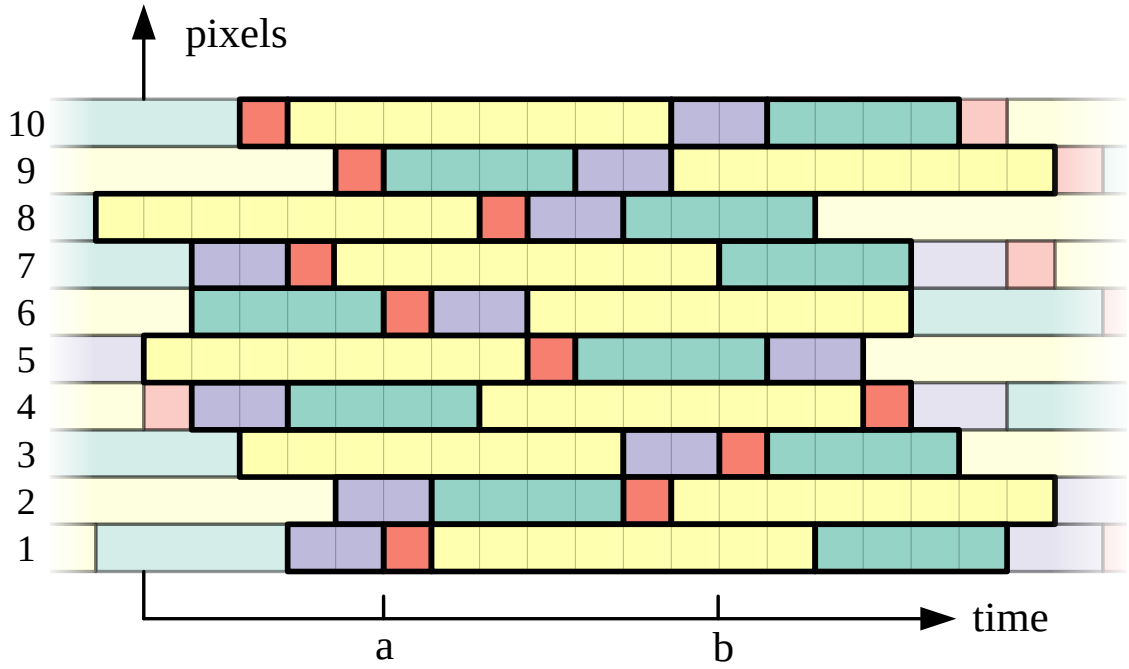
Temporal super-resolution difficult

- Inversion of sampling operation is ill-posed

Our Sampling Scheme

Random permutation and offset of 4 exposures (1, 2, 4, 8)

Only pixels at end of their exposures are read out each frame



100% light throughput, HDR capability

Reconstruction Approach

Exploit spatial and temporal redundancy

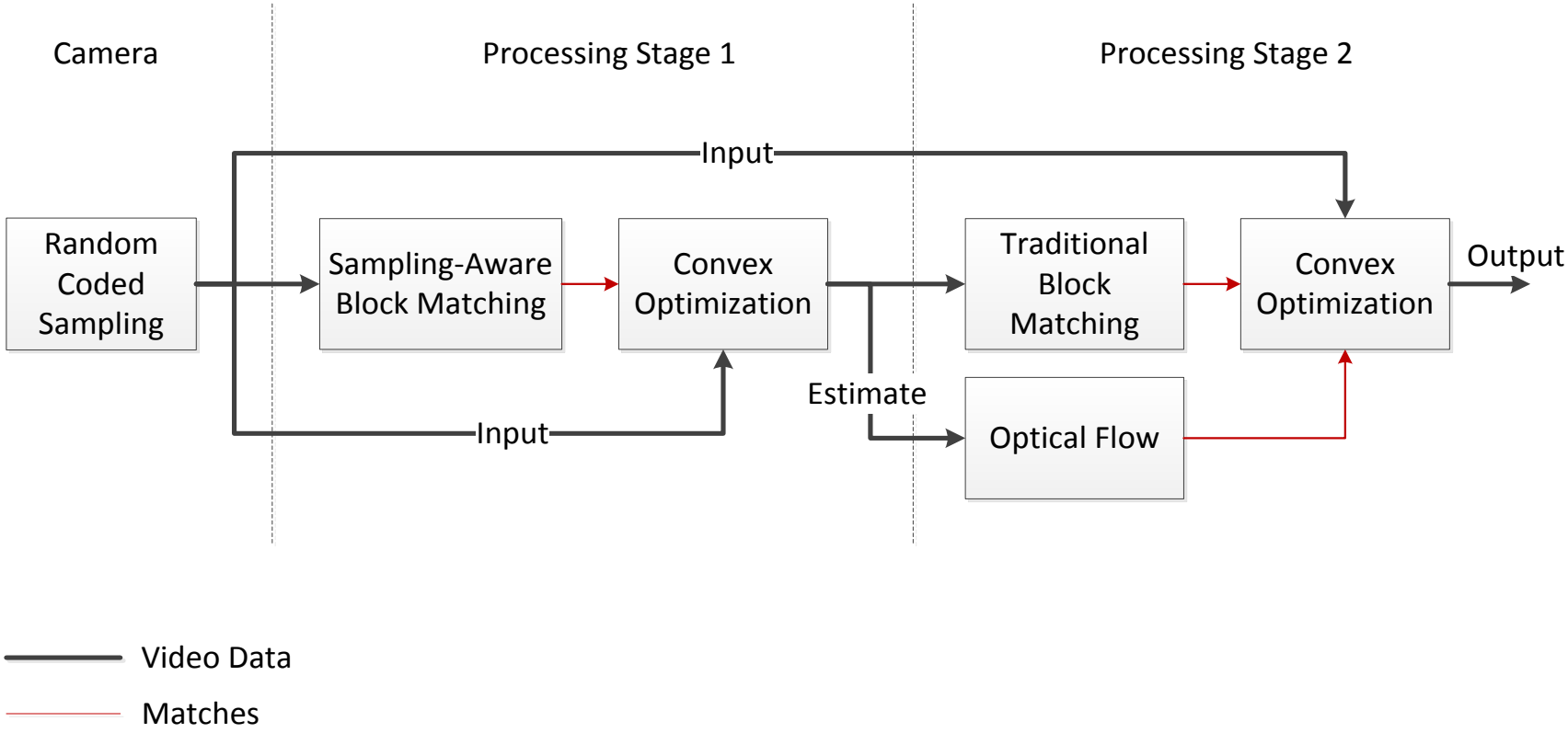
- Block matching and optical flow to find similar patches
- Matches have different sampling patterns:
  - “Deblur” longer exposures using matched shorter exposures
  - Increase dynamic range by combining different exposure times

Use convex optimization to reconstruct high-speed output from sampled input and block matches

- Straightforward method for solving, no local minima

No solving for spatially-varying blur kernels

Algorithm Overview



Block Matching

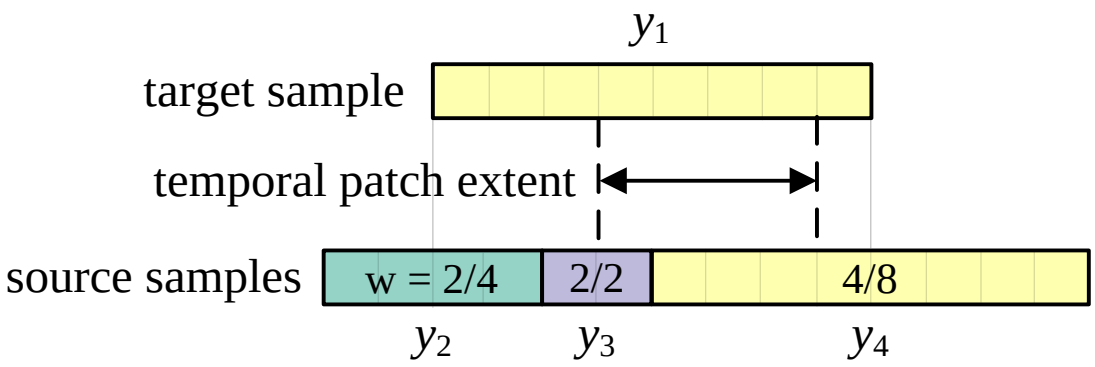
Use 3d space-time patches

Brute force search for *k*-nearest patches

- Restricted to spatiotemporal window around reference patch

Reference and candidate patches may have different sampling patterns

- Resample/blur the patches to match exposures



Convex Optimization

Problem: Given sampled input video y and block matches, reconstruct high-speed HDR output x

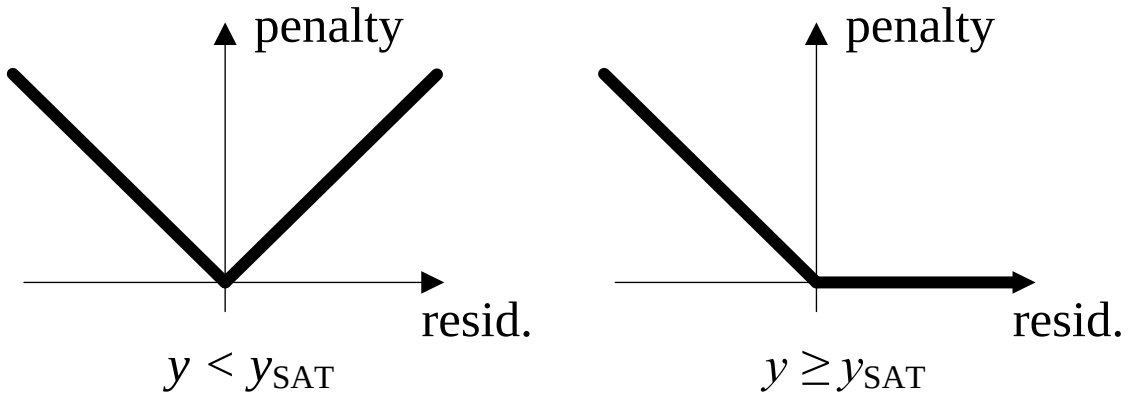
Objective Function:

$$\sum_i \sum_{j \in G_i} w_{ij} \left(\frac{\tau_{\max}}{\tau_j} \| S_{i|j} x - y_j \|_{1^*} + \gamma \| x_i - x_j \|_1 \right)$$

i	reference location
G_i	set of matches
j	match location
w_{ij}	constraint weight
τ_j	exposure time
$S_{i\|j}$	sample x at location i to match pattern at j
γ	regularization weight
$\|\|.\|\|_{1^*}$	one-sided penalty function

Convex Optimization

One-sided penalty function for saturated samples



If input is saturated, only penalize darker estimates

L1 norm used for robustness to bad matches

Convex Optimization

Solve using Alternating Direction Method of Multipliers (ADMM)

- Rewrite objective function:

$$\|Ax - b\|_{1^*} + \gamma\|Fx\|_1$$

  - A sparse matrix with weighted $S_{i|j}$ terms as rows
  - b column vector of weighted y_j inputs
  - F sparse matrix with rows of form [w_{ij} $-w_{ij}$]
- Reformulate as constrained convex optimization:

$$\text{minimize } \|z_1\|_{1^*} + \|z_2\|_1$$

$$\text{subject to } \begin{bmatrix} A \\ \gamma F \end{bmatrix} x - \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} b \\ 0 \end{bmatrix}$$

Simulation

Capture high-speed video with Point Grey Grasshopper

- 200 frames per second
- 14-bit sensor
- Full duty cycle (no gaps between exposures)

Simulate coded sampling by adding pixel values together based on sampling pattern

Add shot noise and read noise

Simulate A/D conversion by quantizing to 8 bits and clamping saturated values

Results

Coded Sampling | Our Result | Ground Truth

4x Exposure | 1x Exposure | Denoised (CVBM3D) 1x Exposure

Results

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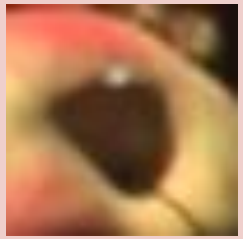
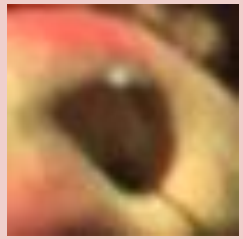
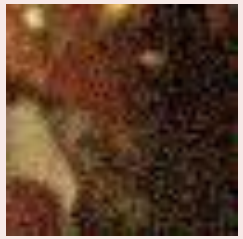
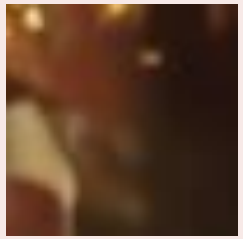
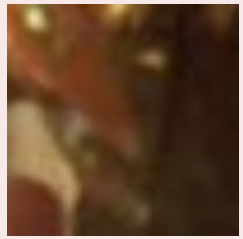
4x Exposure | 1x Exposure | Denoised (CVBM3D) 1x Exposure

Results

	1x Exposure	Denoised 1x Exposure (CVBM3D)	Our result	Ground truth
Frame 14				
Frame 70				

Results

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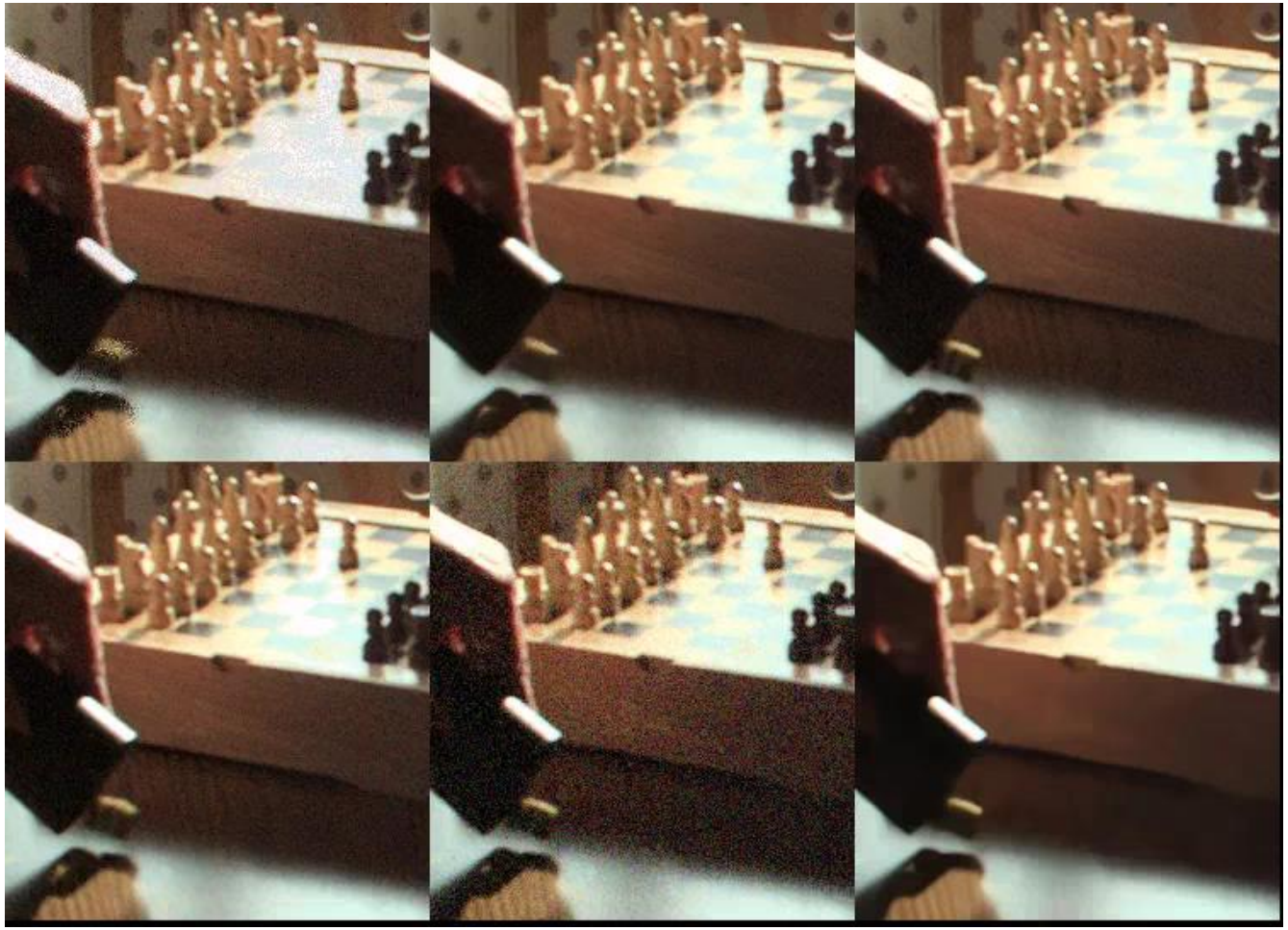
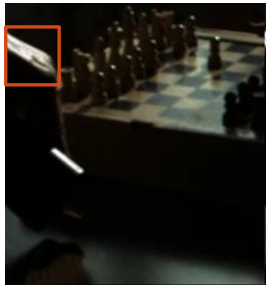


Convergence

ADMM converges slowly in highly saturated regions

- Fewer unsaturated matches



25 iterations	50 iterations	75 iterations	100 iterations	Ground truth
				

Results

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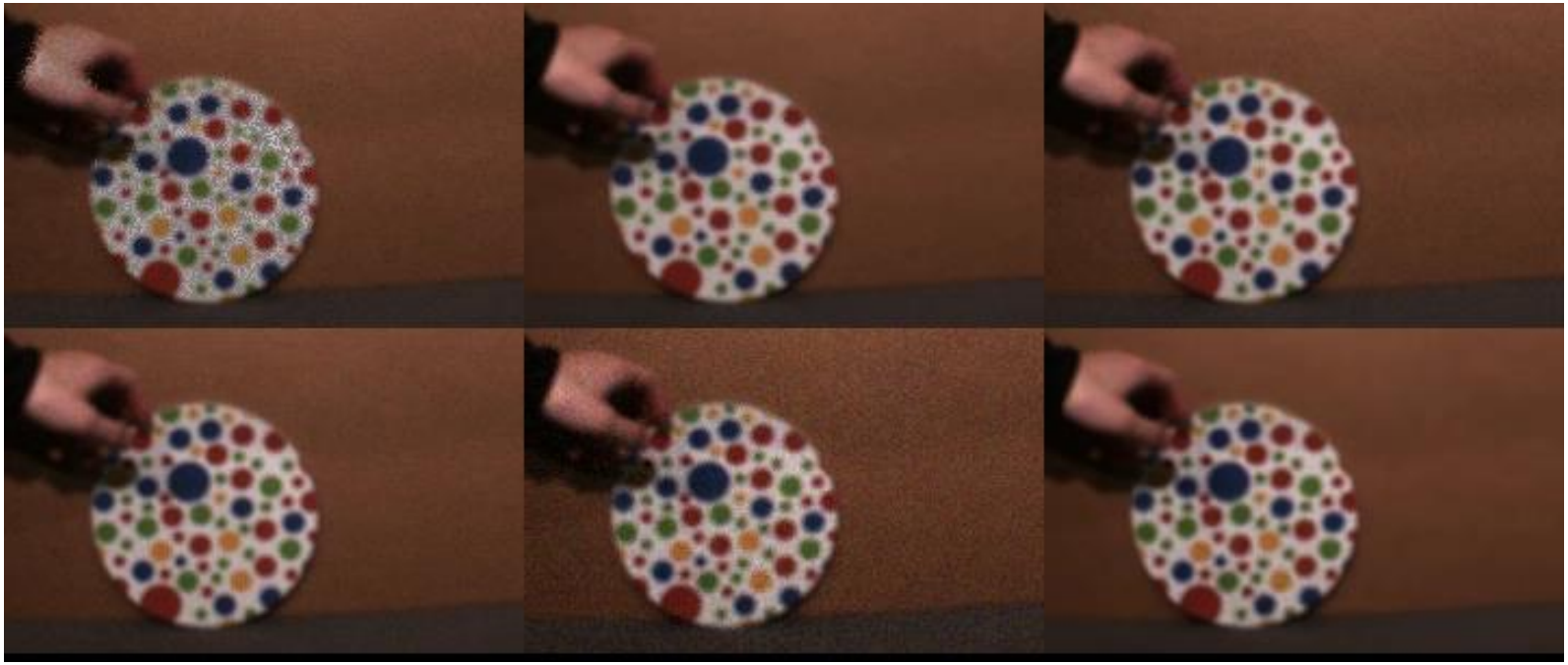
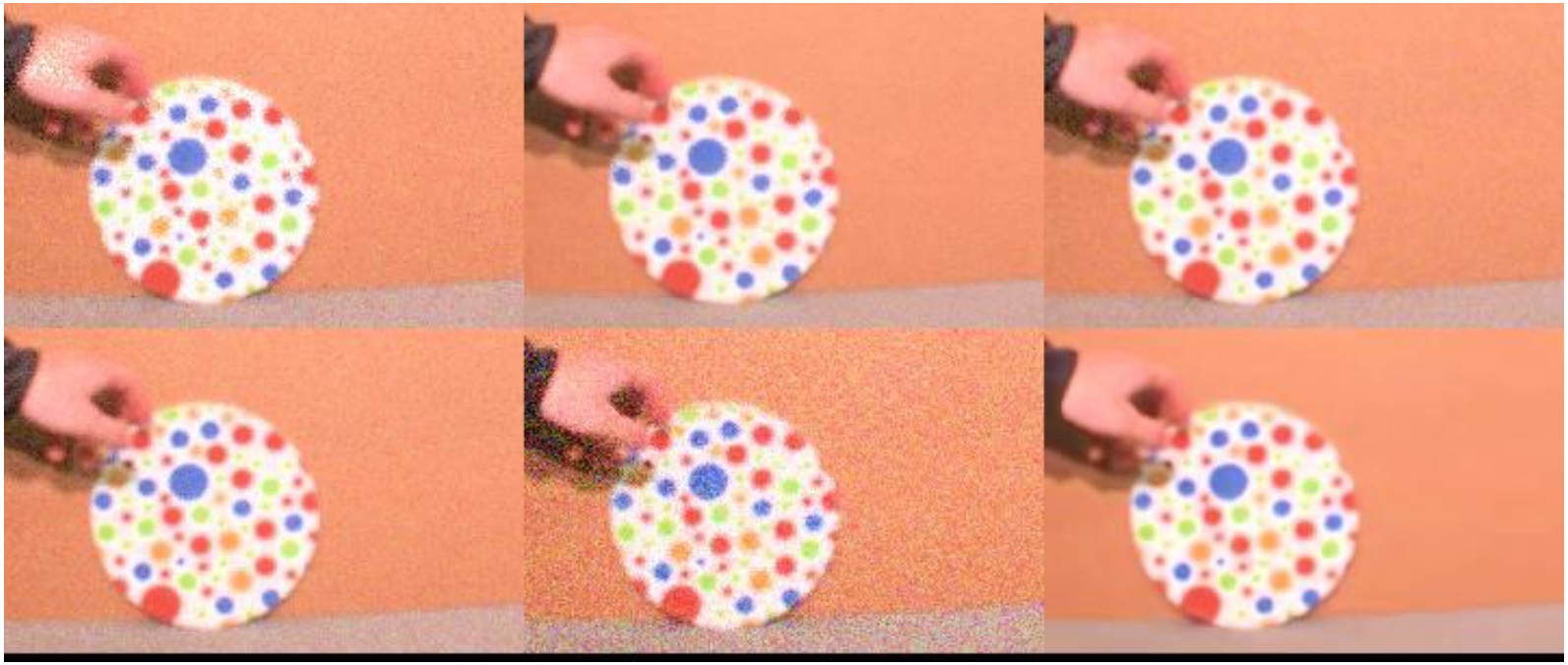


4x Exposure | 1x Exposure | Denoised (CVBM3D) 1x Exposure

Results

Coded Sampling | Our Result | Ground Truth



4x Exposure | 1x Exposure | Denoised (CVBM3D) 1x Exposure

Conclusion

Main Contributions

- Higher frame rate AND higher dynamic range
- Sampling scheme
  - Implementable on single chip
  - 100% light throughput

Future Work

- Avoid constructing global sparse system
- Different types of regularization
- Support for Bayer pattern input
- Hardware implementation