DMD Implementation of a Single Pixel Camera Based on Compressed Sensing

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Pressure is on Digital Signal Processing

• Shannon/Nyquist sampling theorem
  – no information loss if we sample at 2x signal bandwidth

• DSP revolution:
  *sample first and ask questions later*

• Increasing *pressure* on DSP hardware, algorithms
  – ever faster sampling and processing rates
  – ever larger dynamic range
  – ever larger, higher-dimensional data
  – ever lower energy consumption
  – ever smaller form factors
  – multi-node, distributed, networked operation
  – radically new sensing modalities
  – communication over ever more difficult channels
Sensing by *Sampling*

- Long-established paradigm for digital data acquisition
  - *sample* data (A-to-D converter, digital camera, ...)
  - *compress* data (signal-dependent, nonlinear)
  - brick wall to performance of modern acquisition systems
Sparsity

- Many signals can be sparsely represented in some representation/basis (Fourier, wavelets, ...)

\[ N \text{ pixels} \]

\[ K \ll N \text{ large wavelet coefficients} \]

\[ N \text{ wideband signal samples} \]

\[ K \ll N \text{ large Gabor coefficients} \]
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![Diagram of data processing pipeline](image)

- $f$ → sample $\rightarrow N \gg K \rightarrow$ compress $\rightarrow K \rightarrow$ transmit
- *sparse* wavelet transform

- $K$ → decompress $\rightarrow N \rightarrow \hat{f}$
From Samples to *Measurements*

- Shannon/Nyquist sampling theorem
  - must sample at 2x signal bandwidth
  - *too pessimistic for many signal classes*
  - worst case bound for *any* bandlimited data

- **Compressive sensing (CS) principle**
  [Donoho; Candes, Romberg, Tao; Rice, ...]

  "sparse signal statistics can be recovered from a small number of *non-adaptive linear measurements*

- *integrates sensing, compression, processing*
- enables sub-Nyquist "measuring"
- leverages new *sparse* data representations
- based on new *uncertainty principles* that extend Heisenberg’s
- features *random* projections/measurements
- signal recovery via *optimization* (linear programming)
Incoherent Bases

- Spikes and sines (Fourier)  
  \[ \psi = \mathbf{I} \]

- (Heisenberg)  
  \[ \Phi = \text{idct}(\mathbf{I}) \]
Incoherent Bases

- Spikes and “random basis”

\[ \Psi = I \quad \Phi = \text{randn}(N, N) \]
Incoherent Bases

- Spikes and “random sequences” (codes)

\[ \Psi = I \]
Incoherent Bases
Sensing by *Sampling*

- Long-established paradigm for digital data acquisition
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Compressive Sensing

- Measure linear projections onto *incoherent* basis where data is *not sparse*
  - random "white noise" is *universally incoherent*
  - mild "over-sampling" \( M \approx O(K \log(N/K)) \ll N \)

- Reconstruct via nonlinear optimization (linear programming)
CS Hallmarks

- CS changes the rules of the data acquisition game
  - beats the Nyquist limit
  - exploits a priori signal \textit{sparsity} information
  - slogans: “sample less, compute more”

- Universal
  - same random projections / hardware can be used for \textit{any} compressible signal class \textit{(generic)}

- Democratic
  - each measurement carries the same amount of information
  - simple encoding
  - robust to measurement loss and quantization
  - natural “dimensionality reduction” for posing \textit{vision} tasks

- Asymmetrical (most processing at decoder)

- Random projections weakly encrypted
DLP/DSP CS Camera

- **Single photon detector**
  - Low-cost, fast, sensitive optical detection

- Image encoded by PMM and random basis

- Random pattern on DMD array

- Compressed, encoded image data sent via RF for reconstruction

- DSP

- Image reconstruction
TI Digital Micromirror Device (DMD)

DLP 1080p --> 1920 x 1080 resolution
(Pseudo) Random Optical Projections

• Binary patterns are loaded into mirror array:
  – light reflected towards the lens/photodiode (1)
  – light reflected elsewhere (0)
  – pixel-wise products summed by lens

• Pseudorandom number generator outputs measurement basis vectors

• Mersenne Twister [Matsumoto/Nishimura, 1997]
  – Binary sequence (0/1)
  – Period $2^{19937} - 1$
Single Sensor Camera

Potential for:

• new modalities beyond what can be sensed by CCD or CMOS imagers

• low cost

• low power
DLP/DSP CS Camera

Object
LED (light source)
Photodiode circuit
Lens 2
Lens 1
DMD+ALP Board
DLP/DSP CS Camera

- Object
- LED (light source)
- Lens 1
- Lens 2
- Photodiode circuit
- DMD+ALP Board

The diagram shows the setup of a DLP/DSP CS Camera, with labels indicating the various components involved in the system.
DLP/DSP CS Camera

- Object
- LED (light source)
- Lens 1
- Lens 2
- Photodiode circuit
- DMD+ALP Board
First Image Acquisition

ideal 4096 pixels

image at DMD array

205 wavelets

820 random meas.

409 wavelets

1638 random meas.
CS Video Imaging

- Incoherent projections in space-time (random)
- Reconstruct using 3-D wavelets (localized in space-time)
original 64x64x64

frame-by-frame 2-D CS recon
20000 coeffs, MSE = 18.4

3-D wavelet thresholding
2000 coeffs, MSE = 3.5

joint 3-D CS recon
20000 coeffs, MSE = 3.2

M. Wakin & R. Baraniuk
Color CS Camera

Color Filter Wheel

Red Filter

Green Filter

Blue Filter

Original

Reconstructed
Color Imaging with CS Camera

Mandrill 32x32

Mandrill 64x64
Multispectral/Hyperspectral Imaging

Carousel of Differing Photodiodes

- U.V. Enhanced Silicon Detectors
- Blue Enhanced Silicon Detectors
- Silicon Carbide U.V. Detectors
- Visible Light Detectors
- Daylight Filter Detectors
- GaAlAs Photodiodes
- CdS Photoconductive Cells
- *relative responsivity
- 1.06 Micron Detectors

Broadband vs. Narrow-Region (**Near-IR/UV**)

ala the Foveon Image Array

Dual Photodiode Sandwich

ADVANCED PHOTONIX, INC.

SD138-11-31-211
Silicon PIN Photodiode Sandwich Detector

UDT Sensors, Inc.
More Complex Photodetectors

http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/photomultipliers.html
Multisensor DMD Camera
Conclusions

• **Compressive sensing**
  - exploit image sparsity information; beat Nyquist
  - based on new uncertainty principles
  - “sample smarter”, “universal hardware”
  - integrates sensing, compression, processing

• **Ongoing research**
  - new kinds of *imagers*: image and video
  - *information scalability* for vision applications
    reconstruction > approximation > estimation > classification > detection
  - multi-camera *light field* acquisition and processing (3-D)
  - *fast algorithms* (DSP)
  - *R/D* analysis of CS (quantization)
  - new “*analog-to-information*” converters (analog CS)

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