Coded Two-Bucket Sensors for Active and Passive Imaging

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Abstract I will discuss our recent progress in designing *coded two-bucket sensors*, a new family of programmable CMOS image sensors that combine the advantages of coded-exposure and multi-tap imaging. Each pixel in a coded two-bucket (C2B) sensor consists of two charge collection sites—buckets—whose activity can be programmed independently at each pixel and toggled many times during a single exposure. A key performance metric in this family of sensors is their *subexposure rate, i.e.,* the maximum speed at which a pixel's active bucket can be toggled. We have achieved orders-of-magnitude improvement in this rate over the past six years, with our latest sensor supporting more than 1000 subexposures per video frame readout when operating at 30 fps, as well as the ability to control bucket activities adaptively. I will show our initial experiments with this sensor in a variety of computational imaging applications—simultaneous direct/indirect imaging, snapshot structured-light imaging, snapshot multi-spectral imaging, high-dynamic range imaging—and discuss the broader opportunities this class of sensors opens for active 2D and 3D imaging: conferring robustness to indirect light; enabling operation in strong sunlight; offering improved visibility through skin and other scattering media; and revealing the scattering and refractive properties of everyday objects and materials.

Keywords: coded-exposure imaging, multi-tap sensors, snapshot HDR imaging, snapshot video acquisition, structured-light triangulation, epipolar-only imaging

References

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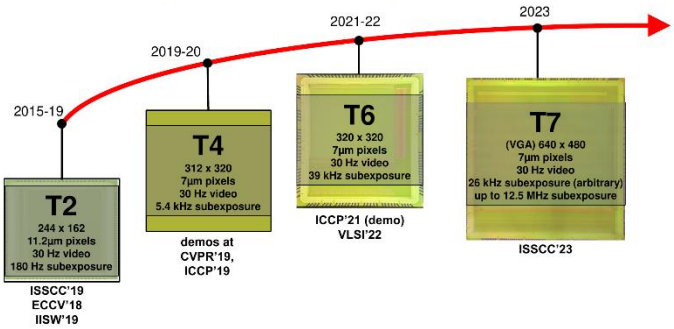
The Toronto Coded Two-Bucket Cameras

Cameras for programmable, light-efficient, high-speed, adaptive coded imaging



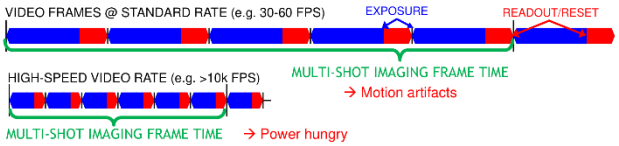
Motivation

✓ Multi-shot imaging: essential for many imaging tasks

✗ Motion artifacts: e.g., blur, blur non-uniformity, inter-frame variability

✓ High-frame-rate cameras: avoid motion artifacts

✗ High read noise and high power dissipation of the ADC



Motivation

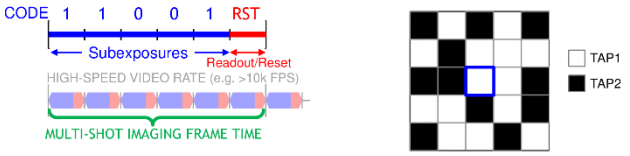
✓ Per-pixel coding: programmable photo-generated charge sorting

✓ Enables single-shot computational imaging → reduced motion artifacts

✓ Multiple fast captures and tap-wise accumulation → no extra read noise

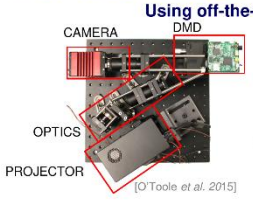
✓ Single high-precision video-rate readout → no extra ADC power

✓ Energy-efficient low-precision subframe-rate readout → adaptive exposure coding

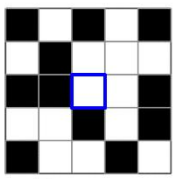


Per-Pixel Coded-Exposure: Existing Solutions

Using off-the-shelf components



Example pixel code



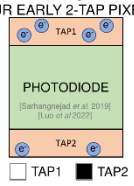
✗ Bulky
✗ Expensive
✗ Limited optical signal fidelity
✗ Single-tap implementation
→ light is lost

✗ Not per-pixel programmable
✗ Mechanical alignment with light sources very challenging
✗ Single-tap implementation
→ light is lost

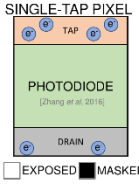
Per-Pixel Coded-Exposure: CMOS Solutions

Integrated CMOS solutions

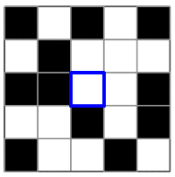
OUR EARLY 2-TAP PIXEL



SINGLE-TAP PIXEL



Example pixel code



✓ Compact system
✓ Inexpensive
✓ Per-pixel control

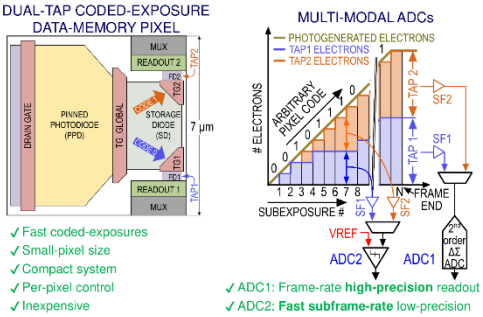
✓ No photo-generated charges are lost

✗ In-pixel PMOS
→ slower performance

✗ Single-tap implementation
→ light is lost

✗ Large in-pixel control
→ large pixel

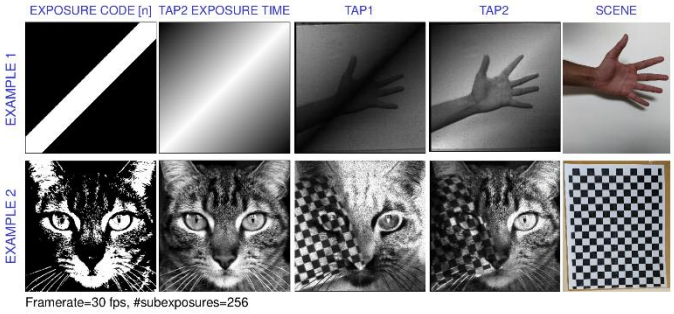
Per-Pixel Coded-Exposure: Our Latest Sensor



- ✓ Fast coded-exposures
- ✓ Small-pixel size
- ✓ Compact system
- ✓ Per-pixel control
- ✓ Inexpensive

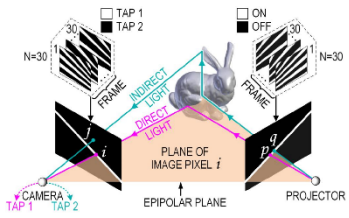
- ✓ ADC1: Frame-rate **high-precision** readout
- ✓ ADC2: **Fast subframe-rate** low-precision

Example: Coded-Exposure Imaging



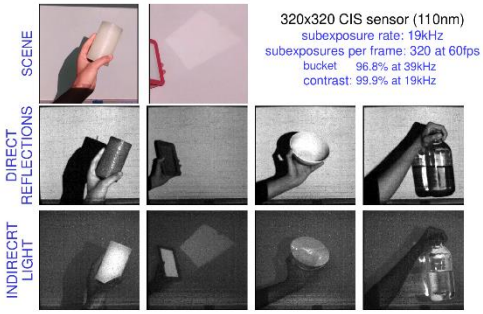
Framerate=30 fps, #subexposures=256

Single-Shot Simultaneous Direct & Indirect Imaging

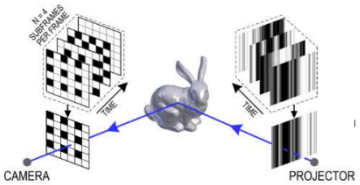


- Goal
  - Simultaneously capture direct and indirect video at 30fps
- Camera Configuration
  - Epipolar patterns
  - 1/60s exposure per frame
  - Synchronized with projector
- Projector Configuration
  - Raster scanning projector
  - Projecting at 60fps

Single-Shot Simultaneous Direct & Indirect Imaging

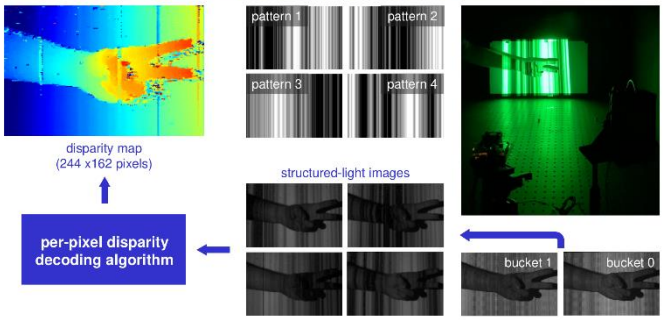


Single-Shot Structure Light 3D Imaging

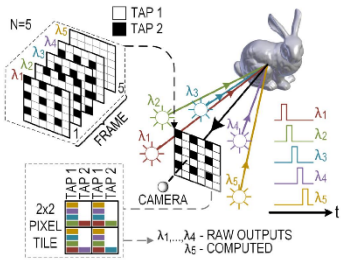


- Goal
  - Find optimal illumination patterns
  - Disparity: proportional to 1/depth
  - Video rate output
- Camera Configuration
  - 4 Bayer-like mosaic patterns
  - 30ms exposure per frame
- Projector Configuration
  - Synchronized with camera
  - 4 programmable patterns

Single-Shot Structure Light 3D Imaging

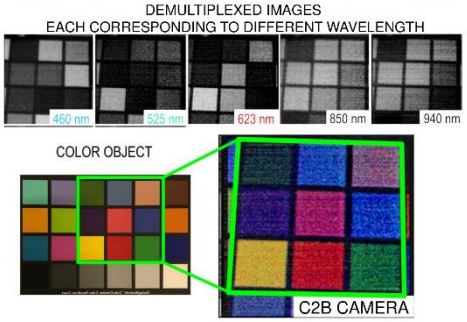


Single-Shot Multi-Spectral Imaging

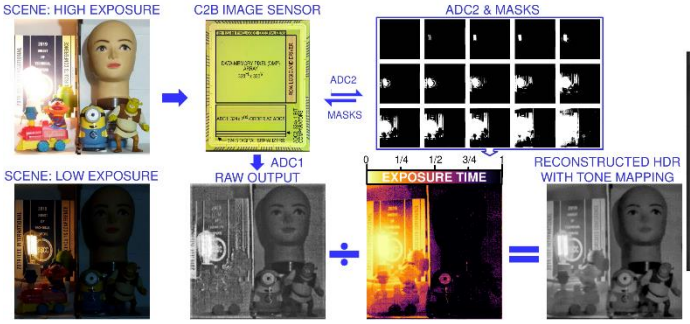


- Goal
  - Acquire images at programmable # of spectral bands
  - Video rate output
- Camera configuration
  - 5 Bayer-like mosaic patterns
  - 30ms exposure, 5 subexposures
- Illumination configuration
  - 5 LEDs of different wavelengths
  - Synchronized with the camera

Single-Shot Multi-Spectral Imaging



Subframe-Rate Scene-Adaptive HDR



Subframe-Rate Scene-Adaptive HDR