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Seeing in the dark: A photon-counting camera system developed from a crossed-strip detector

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What does one do with a photon-counting camera system?

- Low-light imaging of moving targets and dynamic scenes
- Lidar
- Astronomy

Outline

- **Low-light imaging technologies**
- **Photon-counting imaging camera**
- **The next-generation photon-counting imaging camera: the crossed-strip (XS) sensor**
- **Analysis of data from the XS sensor anode channel**
- **Determination of photon time and position**

- **Pulsed x-ray source and nanocomposite scintillators**

Charge-coupled devices (CCDs) and active-pixel sensors (CMOS sensors)

- Cheap
- Big
- High efficiency
- Framing cameras with separate data collection and data readout phases
- Use a serial form of readout
- Increased read noise with decreased integration time

A CMOS active-pixel sensor

<http://en.wikipedia.org/wiki/File:Matrixw.jpg>

CCD working analogy

A 3 by 3 array of buckets (pixels) with vertical and horizontal conveyor belts (CCD shift registers) that transfer water (electrons) to a measuring container (amplifier).

Raindrops == Photons turning into photoelectrons

Detector Issues:

Read Noise == Uncertainty in water height in measuring container

Dark Current == Water leaking into buckets from outside

When running the “conveyor belts” fast for high time resolution, measurements of single photon “raindrops” in the buckets are difficult.

CCD vertical smear

- If the readout is slow relative to the photon rate, a vertical smear results.
- There are ways to prevent the vertical smear *with trade offs*.

CCD and CMOS: motion reconstruction

- Many photons but the object has an uncertain position

Photon-counting imaging sensor: motion reconstruction

- Few photons but the object has a defined position relative to the sensor

Single-photon counting imaging sensors: NCam

- No pixels, no frames
- <1 ns time resolution
- 80 μm FWHM

Which imaging technology is better?

CCD and CMOS

- Cheap
- Big
- High efficiency
- Increased read noise with decreased integration time
- Data product is image frame
- Uses a frame collection and frame readout cycle
- Accepts simultaneous photons

XDL sensors

- Not cheap
- Moderate size
- Moderate efficiency
- No read noise
- Data product is photon list
- **Uses a serial readout of each photon**
- **Cannot accept simultaneous photons**

The crossed-strip (XS) sensor

- Sensor consists of photocathode, MCP stack for amplification, and a crossed-strip anode
- Design is an improvement on the crossed-delay line sensor
- Produces a list of photon positions and times
- Goals
 - 20 μm FWHM position resolution
 - sub-nanosecond time resolution
 - 10^8 photon/s

Figure courtesy Oswald Siegmund, UC Berkeley

The XS camera system

- Embedded system
- Portable
- Fieldable
- Self-contained except for host computer and power source
- Larger format, higher count rate, better timing resolution, and smaller package may be possible for future XS camera systems

MicroTCA chassis organization

Embedded XS camera system: anode-strip amplifiers

- Low-noise amplifiers with 10 ns shaping time
- Noise baseline is around 1000e⁻ RMS for lowest capacitance channels
- For 250,000 electrons, the SNR for a strip at the center of the charge cloud would be greater than 30 dB

Embedded XS camera system: digitizers

- **Newly-developed 4DSP 16-channel 125-MHz digitizer card for the anode strips**
 - 73 dB SNR
 - 88 dB SFDR
 - 12 effective bits
- **2-GHz single-channel digitizer card for MCP signal**
 - 55 dB SNR
 - 9 effective bits
 - Signal is about 1 ns in width

Anode channel data

- Bench-top system using RD-20 amplifiers and 62.5 MSamples/s digitizer
- Pulses closer than about 32 ns are difficult to separate
- For 10^8 photons/s, 33% of photons fall within 32 ns of another photon
- Faster shaping-time amplifier and faster-sampling ADC needed

Pulse shape variation

- The capacitance varies with the strip length
- Using a $V(t) = At^ke^{-t/\tau}$ pulse model, the pulse shape can be seen not to vary with capacitance
- The edge strips have few counts with divergent forms

Photon time calculation

- Anode strip pulses are correlated into events
- Event time given as amplitude-weighted time average
- Most-probable time offset has standard deviation of 0.71 ns and can be calibrated out
- Smallest possible correlation bin is ~5 ns
- High-speed MCP channel to be used for timing in the embedded system

(a)

(b)

Photon position calculation

- Gaussian charge-cloud shape
- Area is proportional to the measured number of electrons in the charge cloud

- Axis-amplitude ratio provides the possibility for correlation of events close in time

$$\frac{A_{lower}}{A_{upper}} \approx 1.7$$

Image of pinhole mask

- Image created using new six-channel digitizers for prototyping
- Pinholes are 10 μm in diameter
- Measured FWHM diameter is
 - 55 μm for 2 or more pulses per event
 - 47 μm for 3 or more pulses per event
- No focus certainty

First results from 16-channel digitizer boards

Charge-cloud widths

- Fixing the charge-cloud width is desirable computationally
- Within the limits of the statistics in the data recorded so far, there is no significant loss of position resolution to fixing the width

Outlook

- Digitization of all 64 anode channels
- Integration of the MCP timing channel
- Collection of data from various images and at various rates
- Determination of the ideal voltage bias of the XS tube
- Examination of time resolution of the system with a pulsed laser

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Pulsed x-ray source

APD time

- Pulsed 5 kV electron gun on an Ag foil
- 23 ns 10-90 risetime

Nanocomposite scintillators

- Combine the benefits of organic and inorganic scintillators
- Embed inorganic particles into an organic matrix
- Mismatched indices of refraction make opaque materials unless the particles are small enough
- Emission mode intensities change with particle size

Scintillator characterization: Low-background gamma response

Scintillator characterization: Compton linearity