Passive Inter-Photon Imaging

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Fig. 6. A schematic diagram of a charge-coupled line imaging device with lateral transfer to eliminate shuttering.
Conventional Image Sensors

Sony to Release Large Format CMOS Image Sensor with Global Shutter Function and Industry’s Highest Effective Pixel Count of 127.68 Megapixels

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Conventional Image Sensor Pixel

- Photons
- Random arrivals
- Sensor bucket
- Measured signal
- Light
- $T$ (fixed exposure time)
Conventional Image Sensor Pixel

measured signal
Conventional Image Sensor Pixel

low brightness

measured signal
Conventional Image Sensor Pixel

Medium brightness

Measured signal
Conventional Image Sensor Pixel

high brightness

measured signal
Conventional Image Sensor Pixel

- Low flux: sensor bucket contains a few measured signals, resulting in a noisy signal.
- High flux: sensor bucket contains many measured signals, leading to a saturated signal.
Photon Arrival Timelines
Photon Arrival Timelines
Photon Arrival Timelines

Fixed exposure time (T)
Photon Arrival Timelines

Fixed exposure time (T)

low
Photon Arrival Timelines

Fixed exposure time (T)

Random inter-photon times
Photon Arrival Timelines

Fixed exposure time (T)
Photon Arrival Timelines

Fixed exposure time (T)

x

y

time

high
Flux from Inter-Photon Timing?

Fixed exposure time (T)

Brightness \propto \frac{1}{\text{average inter-photon time}}
Inter-Photon Imaging in Practice
Measuring Inter-Photon Timing in Practice

Inter-Photon Single-Photon Avalanche Diode (IP-SPAD)

Dead time ($\tau_d$)
\[ \hat{\Phi} = \frac{1}{\bar{X} - \tau_d} \]

**IP-SPAD: Flux Estimator**

- \( \hat{\Phi} \): IP-SPAD Photon Flux Estimate
- \( \bar{X} \): Average Inter-photon time
- \( \tau_d \): Dead time

Non-linear mapping
IP-SPAD: Signal-to-Noise Ratio (SNR) Analysis

$T = 5\text{ms}$, $\tau_d = 150\text{ns}$
IP-SPAD: Signal-to-Noise Ratio (SNR) Analysis

$T = 5\text{ms}$, $\tau_d = 150\text{ns}$
IP-SPAD: Signal-to-Noise Ratio (SNR) Analysis

Decreasing time resolution

$T = 5\text{ms}, \tau_d = 150\text{ns}$
IP-SPAD: Signal-to-Noise Ratio (SNR) Analysis

$T = 5\text{ms}$, $\tau_d = 150\text{ns}$

>7 orders of magnitude (at 20dB SNR)
Experiment Results
Experiment Tunnel Scene
Experiment Tunnel Scene: Result

Conventional Camera

- Long exposure (5 ms)
- Mid exposure (0.5 ms)
- Short exposure (0.005 ms)

IP-SPAD [Proposed]

- Single exposure (5 ms)
IP-SPAD Imaging with Low Photon Counts
IP-SPAD with Few Photons

What if we only get 1 photon per pixel?
IP-SPAD Imaging with 1 Photon Per Pixel

First-photon Timestamp Image

10^{-10}  

(seconds)  

10^{-6}
IP-SPAD Imaging with 1 Photon Per Pixel

- Raw data
- Bilateral Filtering
- BM3D Denoising
- DNN-based denoising

First-photon timestamp:

$10^{-10}$ to $10^{-6}$ seconds
Implications

IP-SPAD Imaging: SPADs as General-Purpose, Passive Sensors

https://wisionlab.cs.wisc.edu/project/ip-spad/