A Programmable Digital Camera Architecture
Multiple Capture Single Image

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http://smartcamera.stanford.edu/pdc.html
Outline of the Presentation

• Camera architecture lab

• CMOS sensor (PDC ‘98)
  • Pixel-level ADC
  • Programmable features

• Programmable digital camera architectures
  • Transduction
  • Temporal programming: Dynamic range
  • Spatiotemporal: Intensity resolution
Experimental Lab: Overview
Experimental Lab: Sensors

HPMosis
640*512
Experimental Lab: FPGA
Programming overview

Labview | Frame Grabber | Matlab Compiler | Assembly Language

Scene → FPGA Pattern generator
PDC Sensor ‘98

• Pixel-level ADC
• CMOS (4.5 transistors/pixel)
• Feature size: 0.35 µm
• Pixel size: 10 µm
• Light Sensitivity
  • Fill factor: 23 percent
  • QE: 4 percent
Sensor: Pixel-level architecture

- **S0, S1, S2, S3**: Switches
- **RESET**: Reset
- **LATCH**: Latch
- **COMPARATOR**: Comparator
- **C_{storage}**: Storage capacitor
- **RAMP from FPGA**: Ramp from FPGA
- **Open switch to read**
- **Read but continue charging**
Sensor: Quad pixel layout
Programmable Digital Camera Algorithms

- Single Capture temporal integration
- Multiple Capture Single Image (MCSI)
  - Transduction
  - Temporal programming: Dynamic range
  - Spatiotemporal: Intensity resolution
Single Capture: Integration Time

Integration time set by highlights
Single Capture: Digital encoding

Format: integer
Number of bits to encode
$log_2 N_L$
Single Capture: Transduction

![Graph showing digital value vs. intensity for long and short duration](image)

- **Long duration**
- **Short duration**
MCSI: Integration Times

First sample time set by highlights

Final sample time set by lowlights
MCSI: Digital Encoding

3 bit ADC example

Accumulated charge (e)

Time
MCSI: Digital Encoding

\[ dc = L \cdot 2^{-T} \]

Format: floats

Number of bits
\[ \log_2 N_L + \log_2 N_T \]
MCSI: Dynamic range

Multiple integration times increases dynamic range
MCSI: Dynamic Range

Integrated image using DiCarlo Algorithm
MCSI: Transduction

• The FPGA timing and comparator levels can be controlled, so
  – The transduction function can be varied between frames
  – The quantization levels can be selected freely (up to noise considerations)
MCSI: Example Transduction

\[ \gamma = 0.5 \]

\[ \gamma = 1.0 \]

\[ \gamma = 2.0 \]
MCSI: Standard transduction
MCSI: Programmable Transduction

Level method

Timing method
MCSI: Time/Level Tradeoffs

- Better SNR
- More captures
- Optional time/level intensity settings
MCSI: Time/Level Optimization

2-bit device, 25ms Sampling separation
7 bit (linear) device needed

Desired intensity quantization
MCSI: Intensity resolution

Multiple captures permits averaging for better SNR and for better range.
MCSI: Intensity resolution

To improve to intensity resolution we must account for the noise and quantization bins

Adjust comparator  Average frames
MCSI: Frame averaging

Averaging improves intensity resolution, as shown by increased slope
MCSI: Programmable Spatial Resolution

- The electrons collected in groups of four pixels can be read out separately or summed.
- Under low lighting conditions, one might sacrifice spatial resolution to increase sensitivity.
MCSI: Programmable Resolution

Trade spatial resolution against photon sensitivity by combining photons of combination of quarter images

Spatial resolution: 640*512

Spatial resolution: 320*256
MCSI: Spatial estimation

Camera measurements

\[
\begin{pmatrix}
m_1 \\
m_2 \\
m_3 \\
m_4 \\
m_5 \\
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
.25 & .25 & .25 & .25 \\
\end{pmatrix}
\begin{pmatrix}
p_1 \\
p_2 \\
p_3 \\
p_4 \\
\end{pmatrix}
\]

Hi-res mode
16 ms

Hi-sensitivity mode
4 ms

Picture intensity
MCSI: Contrast sensitivity

Single capture

Multiple capture

16 ms

20 ms
MCSI: Contrast sensitivity
MCSI: Simulator

Continuous Contrast Ramp = -0.0225 → 0.0225
Summary and Conclusion

- New sensor technology requires new algorithms
- Programmable to optimize for applications
- CMOS pixel-level ADC
  - Frame rate
  - Memory
  - Integrated processing