Quantitative Study of High Dynamic Range Image Sensor Architectures

Sam Kavusi and Abbas El Gamal
Department of Electrical Engineering
Stanford University
Scene DR > Image Sensor DR

Courtesy Pixim Corporation
DR Extension Methods

Several methods have been developed to extend image sensor DR

Deep submicron CMOS image sensor processes [Wuu ‘01] and vertical integration [Kozlowski ‘02] enable implementation of high DR, high fidelity methods

This work studies four such schemes:

- Time-to-saturation [Lule ‘99, Stoppa ‘02]
- Multiple-capture [Yang ‘99, Kleinfelder ‘01, Bidermann ‘03]
- Asynchronous self-reset with multiple capture [Liu ‘03]
- Synchronous self-reset with residue readout [Bermak ‘02, Rhee ‘03]
How should these methods be compared?

Methods can be partially compared based on their SNR [Yang ’99, El Gamal ’02]:
- Some schemes extend DR but at expense of SNR

This work:
- Quantify SNR for the four schemes
- Consider non-idealities due to implementation, especially due to pixel area constraint
Conventional (Reference) Sensor

- CCD, APS, CTIA

\[ Q_{\text{max}} = 125,000e^- \]
\[ \sigma_{\text{Readout-Ref}} = 5e^- \]
\[ t_{\text{int}} = 30\text{msec} \]

SNR increases as \( i_{\text{ph}} \)

\[ i_{\text{in}} = q\sigma_{\text{Readout}}/t_{\text{int}} \]
SNR increases as \( i_{\text{ph}}^2 \)

\[ i_{\text{max}} = qQ_{\text{max}}/t_{\text{int}} \]
Time-to-Saturation

[Lule ‘99, Stoppa ‘02]

\[ v(t_{\text{int}}) = V_{\text{max}} \]

\[ t = t_{\text{sat}} \]

\[ \hat{i}_{\text{ph}} \propto \frac{V_{\text{max}}}{t_{\text{sat}}} \]
**Time-to-Saturation**

[Lule '99, Stoppa '02]

- \(i_{\text{min}} = q\sigma_{\text{Readout}}/t_{\text{int}}\)
  - Similar to reference sensor
- \(i_{\text{max}}\) and SNR limited by:
  - \(t_{\text{sat}}\) inaccuracy due to comparator noise/delay, time-ramp inaccuracy, \(kTC\) of \(C_{T-\text{Ref}}\) (inaccuracy in \(t_{\text{sat}}\) measured by \(\sigma_{\text{sat}}\))
- \(i_{\text{max}} = qQ_{\text{max}}/\sigma_{\text{sat}}\)
\[ Q_{\text{max}} = 125,000 e - \]
\[ \sigma_{\text{Readout-Ref}} = 5 e - \]
\[ t_{\text{int}} = 30 \text{ msec} \]

\[ \sigma_{\text{sat}} = .0005 t_{\text{int}} \]

\[ \text{DR} = 156 \text{ dB} \]

\[ \sigma_{\text{sat}} = .004 t_{\text{int}} \]

\[ \text{DR} = 136 \text{ dB} \]

SNR drops as \( 1/i_{\text{ph}}^2 \)
Multiple-Capture

[Yang ‘99, Kleinfelder ’01, Bidermann ’03]

\[ v(t_{\text{last-sample}}) = V_{\text{last}} \]
\[ t_{\text{last-sample}} = j t_{\text{capt}} \]
\[ \hat{i}_{ph} \propto V_{\text{last}} / (j t_{\text{capt}}) \]
Multiple-Capture
[Yang ‘99, Kleinfelder ’01, Bidermann ’03]

\[ v(t) \]

\[ \int i_{ph} \]

\[ \text{ADC} \]

\[ \text{Filter} \]

\[ \hat{i}_{ph} \]

\[ \text{Pixel} \]

\[ \text{Capture Clock} \]

\[ v(t_{\text{last-sample}}) = V_1 \]

\[ t_{\text{last-sample}} = t_{\text{int}} \]

\[ \hat{i}_{ph} \propto V_1/t_{\text{int}} \]
Multiple-Capture
[Yang ‘99, Kleinfelder ‘01, Bidermann ‘03]

- $i_{\text{min}} = q\sigma_{\text{Readout}}/t_{\text{int}}$
  - × Pixel-level ADC resolution limited (ADC-ramp, speed/resolution trade-off)
  - ✓ Digital weighted averaging is possible [Liu ’03]
  - ✓ Increasing $t_{\text{int}}$ is possible by motion blur prevention [Liu ’03]

- $i_{\text{max}} = qQ_{\text{max}}/t_{\text{capt}}$
  - ✓ Capture time is very accurate
$Q_{\text{max}} = 125,000e^-$
$\sigma_{\text{Readout–Ref}} = 5e^-$
$t_{\text{int}} = 30\text{msec}$

$\sigma_{\text{Readout}} = 35e^-$
$t_{\text{capt}} = 150\mu\text{sec}$
$\text{DR} = 117\text{dB}$

$\sigma_{\text{Readout}} = 70e^-$
$t_{\text{capt}} = 100\mu\text{sec}$
$\text{DR} = 114\text{dB}$
Asynchronous Self-Reset

[Liou ’02]

\[ v(t) \]

\[ V_{\text{max}} \]

\[ \tilde{i}_{ph} \]

\[ t_{\text{int}} \]

\[ t_{\text{capt}} \]

\[ \tilde{i}_{ph} \propto v'(t) \]
Asynchronous Self-Reset

\[ i_{\text{min}} = q \sigma_{\text{Readout}} / t_{\text{int}} \]
\[ i_{\text{max}} = q Q_{\text{max}} / t_{\text{capt}} \]

- SNR better than MC but with higher DSP cost:
  - ADC resolution limited (ADC-ramp, speed/resolution trade-off)
  - Digital weighted averaging can compensate for it
  - Increasing \( t_{\text{int}} \) is possible by motion blur prevention [Liu ’03]
  - Self-reset accuracy is relaxed

- SNR increasing but limited by gain FPN
\[ Q_{\text{max}} = 125,000e^- \]

\[ \sigma_{\text{Readout-Ref}} = 5e^- \]

\[ t_{\text{int}} = 30\text{msec} \]

\[ \sigma_{\text{Readout}} = 35e^- \]

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\[ \text{DR} = 114\text{dB} \]
Synchronous Self-Reset with Residue Readout

[Beamak '02, Rhee '03]

\[ \hat{\mathit{i}}_{ph} \propto n_{\text{Reset}} + \frac{v(t_{\text{int}})}{V_{\text{max}}} \]
Synchronous Self-Reset with Residue Readout

\[ i_{\text{min}} = q\sqrt{\sigma_{\text{Readout}}^2 + \sigma_{\text{Reset}}^2 / t_{\text{int}}} \]

\( \times \) Reset noise and ADC resolution

\( i_{\text{max}} \) and SNR at high end limited by:

\( \times \) Comparator and self-reset offset accumulation resulting in gain FPN (inaccuracy measured by \( \sigma_{\text{offset}} \))

\( \times \) Underestimation of \( i_{\phi} \) due to signal saturation

\[ i_{\text{max}} = \sqrt{3}qQ_{\text{max}} / t_{\text{clk}} \]
\[ Q_{\text{max}} = 125,000 \text{e}^- \]
\[ \sigma_{\text{Readout-Ref}} = 5 \text{e}^- \]
\[ t_{\text{int}} = 30 \text{msec} \]
\[ \sigma_{\text{Reset}} = 55 \text{e}^- \]
\[ t_{\text{clk}} = 1 \mu\text{sec} \]

SNR drops as \( 1/i_{\text{ph}}^2 \)

\[ \sigma_{\text{offset}} = 0.001 Q_{\text{max}} \]
\[ \text{DR} = 161 \text{dB} \]

\[ \sigma_{\text{offset}} = 0.01 Q_{\text{max}} \]
\[ \text{DR} = 161 \text{dB} \]
## Summary

<table>
<thead>
<tr>
<th>Method</th>
<th>$i_{\text{min}}$</th>
<th>$i_{\text{max}}$</th>
<th>SNR</th>
<th>Pixel Mismatches Effect</th>
<th>DSP</th>
<th>Power</th>
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<tbody>
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<td>++</td>
<td>−</td>
<td>High</td>
<td>Low</td>
<td>Comparator</td>
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<tr>
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<td>− /=</td>
<td>+</td>
<td>+</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Readout/DSP</td>
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<td>High</td>
<td>Readout/DSP</td>
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<tr>
<td>Sync</td>
<td>− −</td>
<td>+++</td>
<td>− −</td>
<td>High</td>
<td>Moderate</td>
<td>Comparator/digital circuits</td>
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</tbody>
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