On the design of sun sensors with event-based operation

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Sun Sensors

Review of the state-of-the-art

Event-based sun sensors

Conclusions
**Sun Sensors**

- Sensors that determine the Sun position (attitude and azimuth) referred to its centroid.

**Sun Sensors Applications**

- **Control of heliostats position.**
  - Accuracy.
  - Precision.

- **Control of solar cells position.**
  - Accuracy.
  - Precision.

- **Navigation systems for spacecrafts and sounding rockets.**
  - Low latency -> Low computational load
  - Accuracy.
  - Precision.
Sun Sensors

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Conclusions
Types of Sun Sensors (I)

Analog sun sensors: the ratio between two photocurrents depend on the sun position.

- Fast operation.
- Sensitive to scene light sources.
- Prone to mismatch and noise.

**Types of Sun Sensors (II)**

Digital sensors: A entire pixel matrix is readout. The sun position is computed by processing this data. Typically APS pixels and frame-based image sensors are employed.

- Reliable and robust to perturbations of external light sources.
- Conventional image sensors can be adapted to operate as a sun sensor.
- Dark pixels are readout and processed.

- The pixel matrix has to be scanned periodically.
- Power consumption is high.
- The exposition time has to be adapted to the illumination conditions.
Digital Sun Sensors

How to avoid data redundancy?

Pixel illumination values are readout in two different steps:
1. The pixel matrix is readout to determine the ROI.
2. All pixels within the ROI are readout and processed to compute the sun position.

- Dark pixels are still readout.
- The pixel matrix has to be scanned periodically if the ROI changes its position.
- An integration time has to be set.
- Dedicated pixel readout circuitry


Sun Sensors

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Conclusions
Event-based Vision Sensors

- Pixels send information asynchronously.
- There is not an integration time.
- Octopus sensors perform a light-to-frequency conversion.
- Dark pixels do not send any information off-chip.
- Fast operation.
- High dynamic range.
Event-based Vision: Optopus Sensor + Pinhole Optics

D=100μm, FD=600μm, T=500μm
**Event-based Vision: Optopus Sensor + Pinhole Optics**

*Only illuminated pixels send out information*

- Interface to monitor the sensor activity
- Pixels response
- Example: 70dB intra-scene dynamic range
**Event-based Vision: Optopus Sensor + Pinhole Optics**

**Sensor operation and centroid computation**

\[
\theta = \arctan \left( \sqrt{W \cdot (x - x_c)^2 + L \cdot (y - y_c)^2} \right) / FD
\]

\[
\phi = \arctan \left( \frac{L \cdot (y - y_c)}{W \cdot (x - x_c)} \right)
\]

\[
x = \frac{1}{N_{\text{events}}} \cdot \sum_{i=1}^{N_{\text{events}}} x_i
\]

\[
y = \frac{1}{N_{\text{events}}} \cdot \sum_{j=1}^{N_{\text{events}}} y_j
\]
Event-based Vision: Optopus Sensor + Pinhole Optics

Time-to-first-spike Operation

- It is possible to resolve the sun position receiving one event.
- Trade-off between the output data flow and error.
**Event-based Vision: Optopus Sensor + Pinhole Optics**

**Sensor’s performance against the art**

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Event Based Luminance Sensor</td>
<td>APS Digital Sensor</td>
<td>APS Digital Sensor</td>
<td>Analog Sun Sensor</td>
</tr>
<tr>
<td><strong>Operation Principle</strong></td>
<td>TFS</td>
<td>Frame-based</td>
<td>Frame-based</td>
<td>Photocurrent Ratio</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>AMS 0.18µm HV</td>
<td>0.18µm 1P4M</td>
<td>UMC 0.18µm</td>
<td>ND</td>
</tr>
<tr>
<td><strong>Power Supply</strong></td>
<td>3.3/5V</td>
<td>3.3/1.8V</td>
<td>3.3/1.8V</td>
<td>ND</td>
</tr>
<tr>
<td><strong>Chip Dimensions</strong></td>
<td>4120µm × 3315µm</td>
<td>5mm × 5mm</td>
<td>11mm × 11mm</td>
<td>6.8mm × 13.8mm</td>
</tr>
<tr>
<td><strong>Number of Pixels</strong></td>
<td>128 × 96</td>
<td>368 × 368</td>
<td>512 × 512</td>
<td>2 pairs of photodiodes</td>
</tr>
<tr>
<td><strong>Pixel Pitch</strong></td>
<td>25µm × 25µm</td>
<td>6.5µm × 6.5µm</td>
<td>11µm × 11µm</td>
<td>NA</td>
</tr>
<tr>
<td><strong>FOV</strong></td>
<td>146°</td>
<td>94°</td>
<td>128°</td>
<td>120°</td>
</tr>
<tr>
<td><strong>Power Consumption</strong></td>
<td>52mW</td>
<td>42.73mW</td>
<td>520mW</td>
<td>ND</td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td>&lt;5ms @ 1klux or lower</td>
<td>10frames/s</td>
<td>10frames/s</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Dynamic Range</strong></td>
<td>&gt;100dB</td>
<td>52dB</td>
<td>ND</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>0.03°</td>
<td>0.004°</td>
<td>&lt;0.005°</td>
<td>ND</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>0.0132° (θ), 0.05° (φ)</td>
<td>0.01°</td>
<td>0.024°</td>
<td>0.15°</td>
</tr>
<tr>
<td><strong>Amount of data</strong></td>
<td>1-100 Events</td>
<td>368 pixels (acquisition mode) + 25 × 25 pixels (tracking mode) = 945 pixels</td>
<td>1 frame (acquisition mode) + ROI (tracking mode)</td>
<td>4 analog voltages to be readout</td>
</tr>
</tbody>
</table>
Event-based Vision: Custom Design

Sensor’s lid arrangement

Sensor’s block diagram

$w=50\mu m$, $d=375\mu m$, $l=2256\mu m$, $h=100nm$
Event-based Vision: Custom Design

Dimensions: 9.5mmx9.5mmx1mm

Sensor test with real sunlight
Event-based Vision: Custom Design

\[ \theta = \arctan \left( \frac{\text{pixel position} - 86}{11.75 \mu m} \right) \]
### Event-based Vision: Custom Design

**Sensor’s performance against the art**

<table>
<thead>
<tr>
<th></th>
<th>Ortega et al. [8]</th>
<th>Xie et al. [4]</th>
<th>Liebe et al. [16]</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Analog Sun Sensor</td>
<td>APS Digital Sensor</td>
<td>APS Digital Sensor</td>
<td>Event Based Sensor</td>
</tr>
<tr>
<td><strong>Operation Principle</strong></td>
<td>Photodiodes Ratio</td>
<td>Frame-based</td>
<td>Frame-based</td>
<td>TFnS</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>ND</td>
<td>0.18μm 1P4M</td>
<td>0.5μm CMOS</td>
<td>AMS 0.35μm opto (C350)</td>
</tr>
<tr>
<td><strong>Power Supply</strong></td>
<td>ND</td>
<td>3.3/1.8V</td>
<td>ND</td>
<td>3V</td>
</tr>
<tr>
<td><strong>Sensor size</strong></td>
<td>(3 x 3 x 1.2) cm</td>
<td>ND</td>
<td>4.2cm³</td>
<td>(9.5 x 9.5 x 1) mm</td>
</tr>
<tr>
<td><strong>Sensor Weight</strong></td>
<td>24 grams</td>
<td>ND</td>
<td>11 grams</td>
<td>0.3 grams</td>
</tr>
<tr>
<td><strong>Pixel array</strong></td>
<td>4 photodiodes</td>
<td>368 x 368</td>
<td>512 x 512</td>
<td>2 x 192 pixels</td>
</tr>
<tr>
<td><strong>Pixel size</strong></td>
<td>0.75mm x 2mm</td>
<td>6.5μm x 6.5μm</td>
<td>12μm x 12μm</td>
<td>9μm x 32μm</td>
</tr>
<tr>
<td><strong>Chip size</strong></td>
<td>6.8mm x 13.8mm</td>
<td>5mm x 5mm</td>
<td>6.1mm x 6.1mm</td>
<td>2.5mm x 2.5mm (8% of area used)</td>
</tr>
<tr>
<td><strong>FOV</strong></td>
<td>120°</td>
<td>±47°</td>
<td>160°</td>
<td>144°</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>ND</td>
<td>0.004°</td>
<td>ND</td>
<td>0.22° ÷ 1.88°</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>0.15°</td>
<td>ND</td>
<td>≈ 0.04°</td>
<td>0.98°(θ) and 0.42°(φ).</td>
</tr>
<tr>
<td><strong>Precision</strong></td>
<td>ND</td>
<td>0.01°</td>
<td>ND</td>
<td>0.104°(θ), 0.061°(φ)</td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td>ND</td>
<td>10fps</td>
<td>30fps</td>
<td>88μs (equivalent to 11.3fps)</td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
<td>ND</td>
<td>42.73mW</td>
<td>30mW</td>
<td>6.3μW</td>
</tr>
</tbody>
</table>
Event-based Vision: Custom Design

- Better resolution.
- Better accuracy
- Less power consumption

- Requires precise optic alignment.
- Design of visión sensor is specific for this application
- Requires dedicated ah hoc optics design too.
Conclusions

- A new approach to implement sun sensors has been developed.
- Dark pixels do not send any information off-chip.
- Fast operation.
- Higher dynamic range operation.
- There is not an integration time.
- Very compressed data flow on TFS mode.
- Two different event-based sensors have been described and compared.