On the design of sun sensors with event-based operation

Juan A. Leñero-Bardallo[1], Lukasz Farian[2], José M. Guerrero-Rodríguez[1], Ricardo Carmona-Galán[3] and Ángel Rodríguez-Vázquez[3]

{juanantonio.lenero}@uca.es

[1]University of Cádiz
Section of Electrical Engineering
Spain

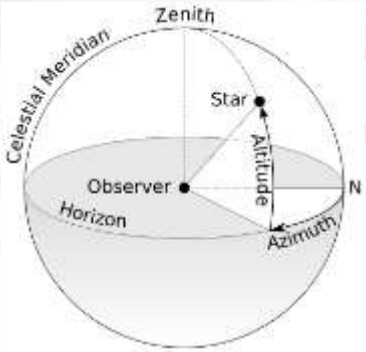
[2]University of Oslo
Department of Informatics
Oslo, Norway

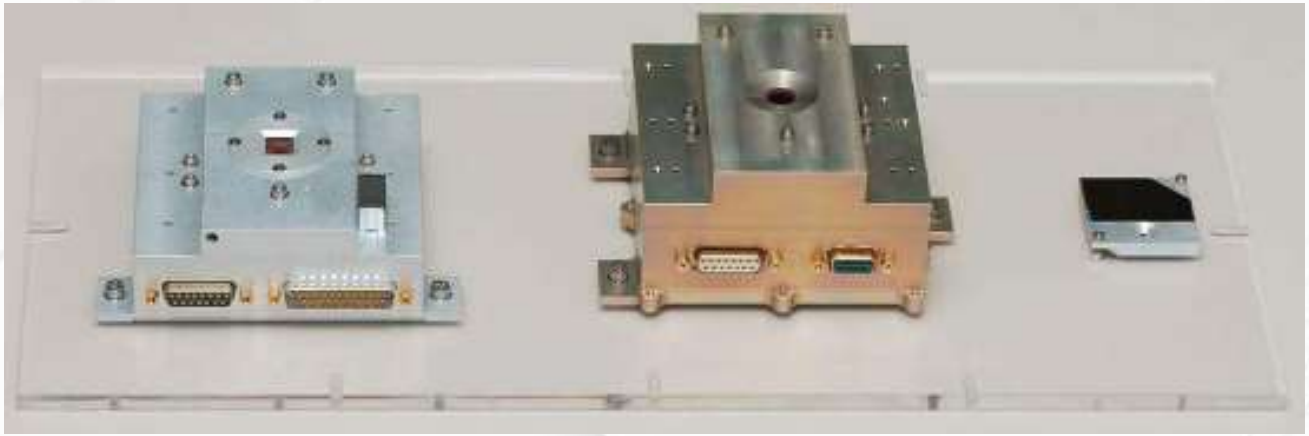
[3]University of Sevilla
Institute of Microelectronics of Sevilla
Spanish Council of Research
Spain

- ***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.**

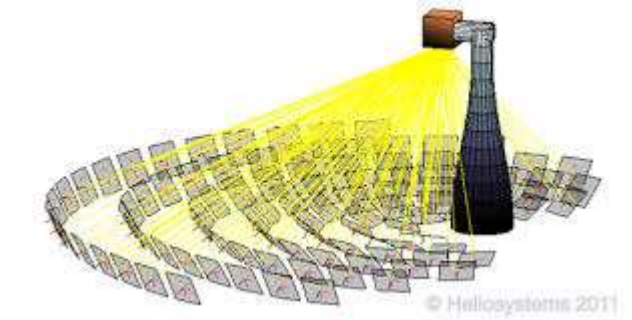




N. Xie and A. J. P. Theuwissen, "*A miniaturized micro-digital sun sensor by means of low-power low-noise CMOS imager*," IEEE Sensors Journal, vol. 14, no. 1, pp. 96–103, Jan 2014.

Sun Sensors Applications

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



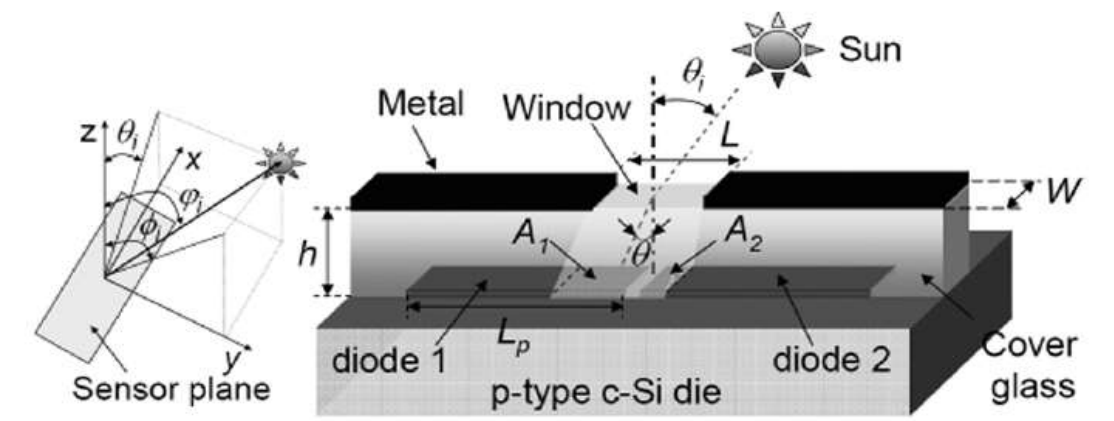
- **Control of solar cells position.**
  - Accuracy.
  - Precision.

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

- ***Sun Sensors***
- ***Review of the state-of-the-art***
- ***Event-based sun sensors***
- ***Conclusions***

Types of Sun Sensors (I)

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

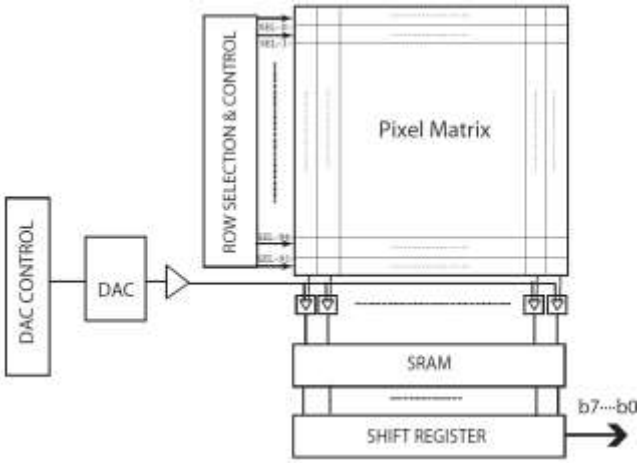


- **Fast operation.**
- **Sensitive to scene light sources.**
- **Prone to missmatch and noise.**

P. Ortega, et al., *"A miniaturized two axis sun sensor for attitude control of nano-satellites,"* IEEE Sensors Journal, vol. 10, no. 10, pp. 1623–1632, Oct 2010.

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.

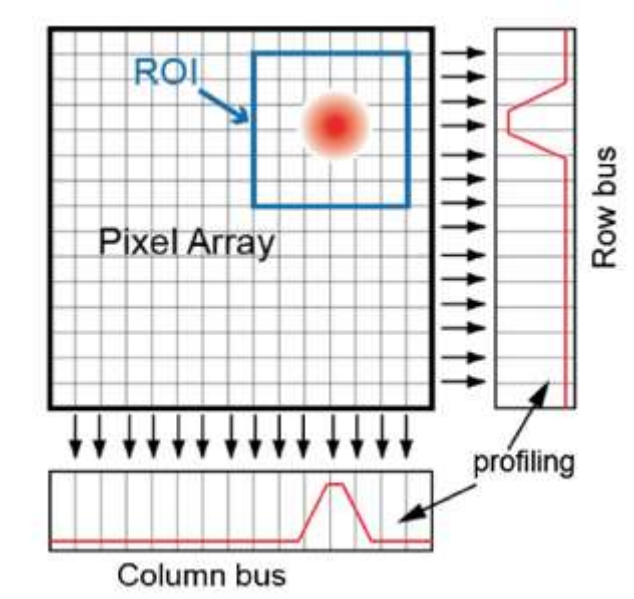


- ✓ **Reliable and robust to perturbations of external light sources.**
- ✓ **Conventional image sensors can be adapted to operate as a sun sensor**
- ✓ **Dark pixels are readout and processed.**

- × **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**

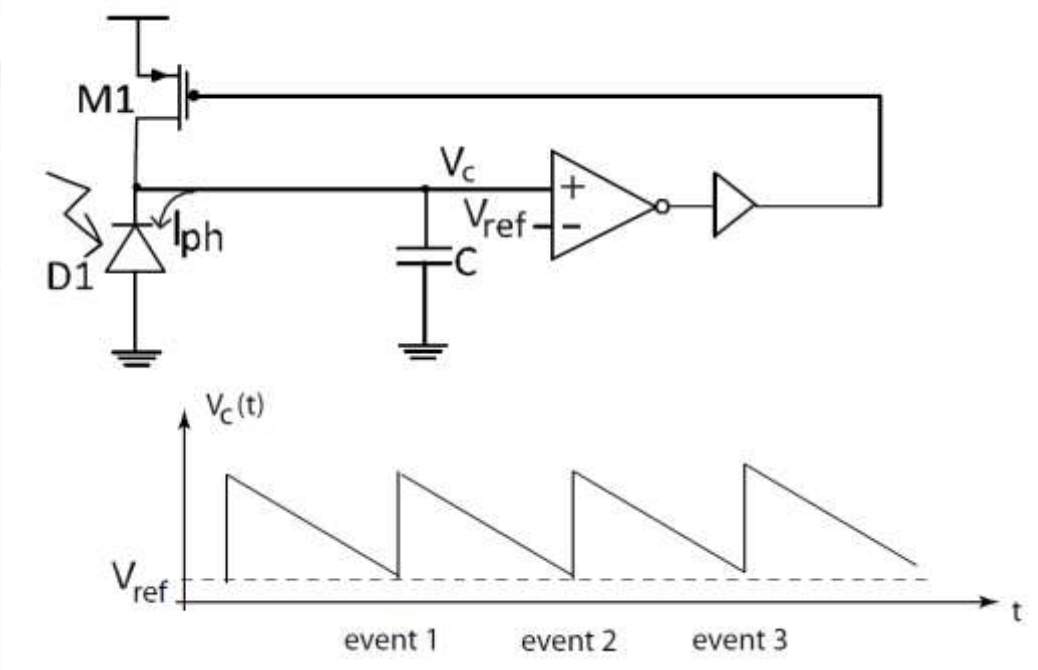
N. Xie and A. J. P. Theuwissen, "*A miniaturized micro-digital sun sensor by means of low-power low-noise CMOS imager*," IEEE Sensors Journal, vol. 14, no. 1, pp. 96–103, Jan 2014.

F. Boldrini et al., *"Attitude sensors on a chip: Feasibility study and breadboarding activities,"* in Proc. 32nd Annu. AAS Guid. Control Conf., February 2009, p. 11971216.

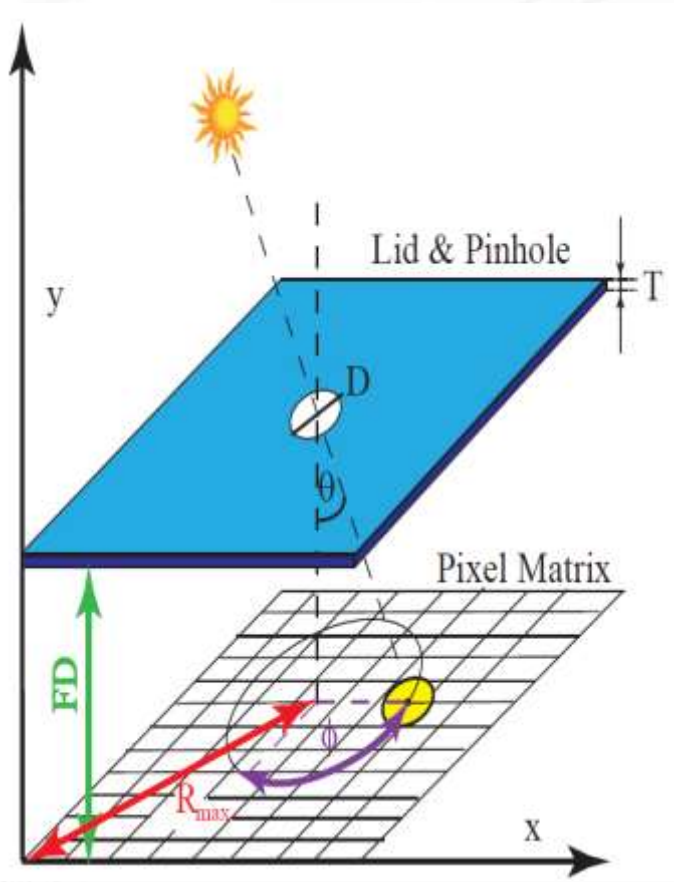
- ***Sun Sensors***
- ***Review of the state-of-the-art***
- ***Event-based sun sensors***
- ***Conclusions***

Event-based Vision Sensors

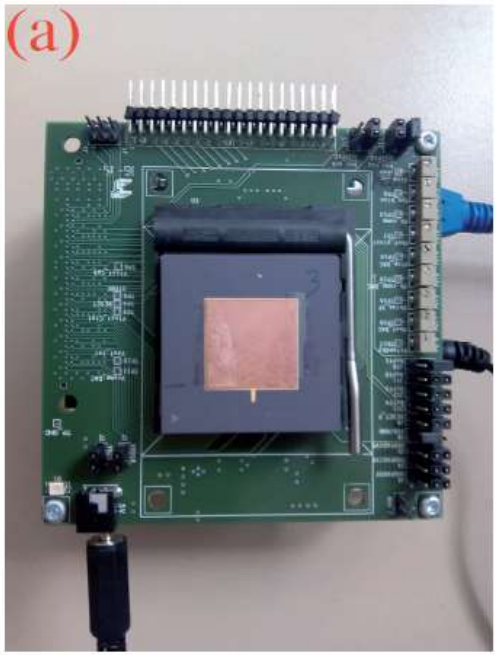
- Pixels send information asynchronously.
- There is not an integration time.
- Octopus sensors perform a light-to-frequency conversion.
- Dark pixels do not send any information off-chip.
- Fast operation.
- High dynamic range.



Event-based Vision: Optopus Sensor + Pinhole Optics



Sensor Implementation

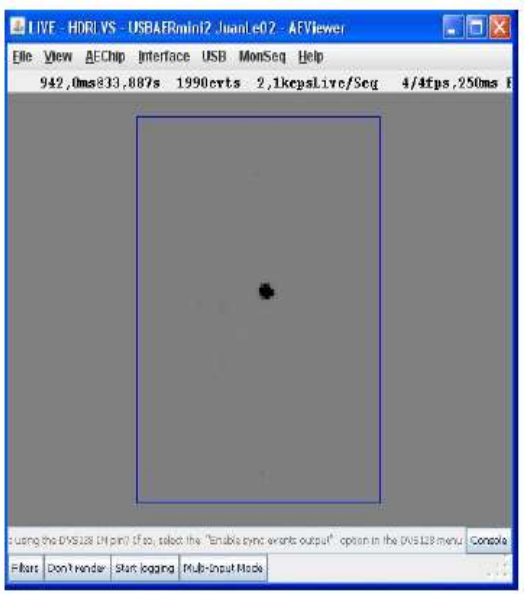


Lid detail

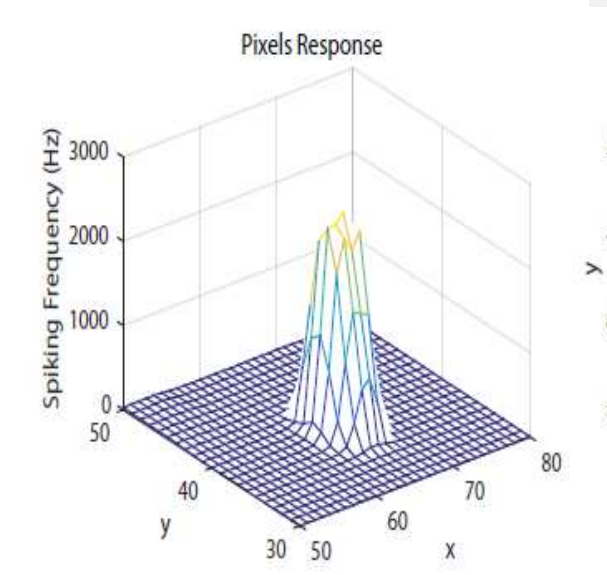
D=100μm, FD=600μm, T=500μm

Event-based Vision: Optopus Sensor + Pinhole Optics

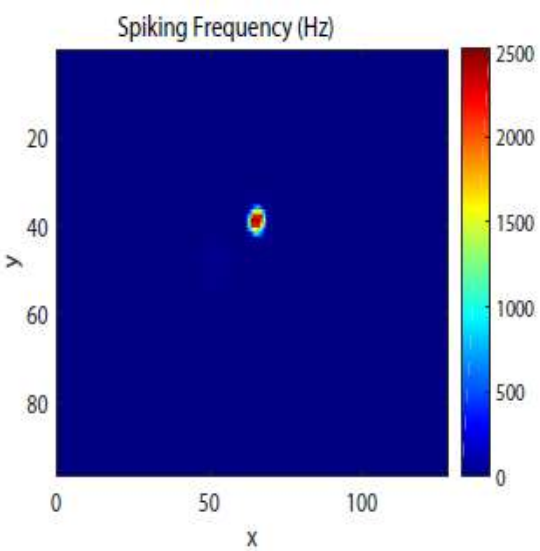
Only illuminated pixels send out information



Interface to monitor the sensor activity



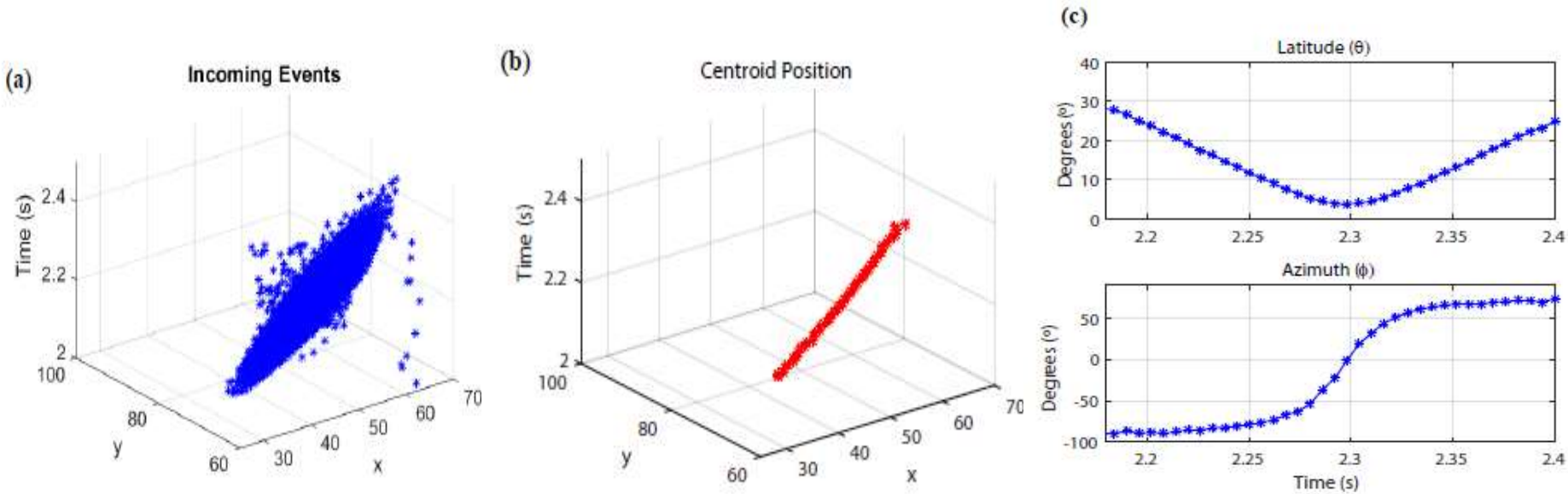
Pixels response



Example: 70dB intra-scene dynamic range

Event-based Vision: Optopus Sensor + Pinhole Optics

Sensor operation and centroid computation



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

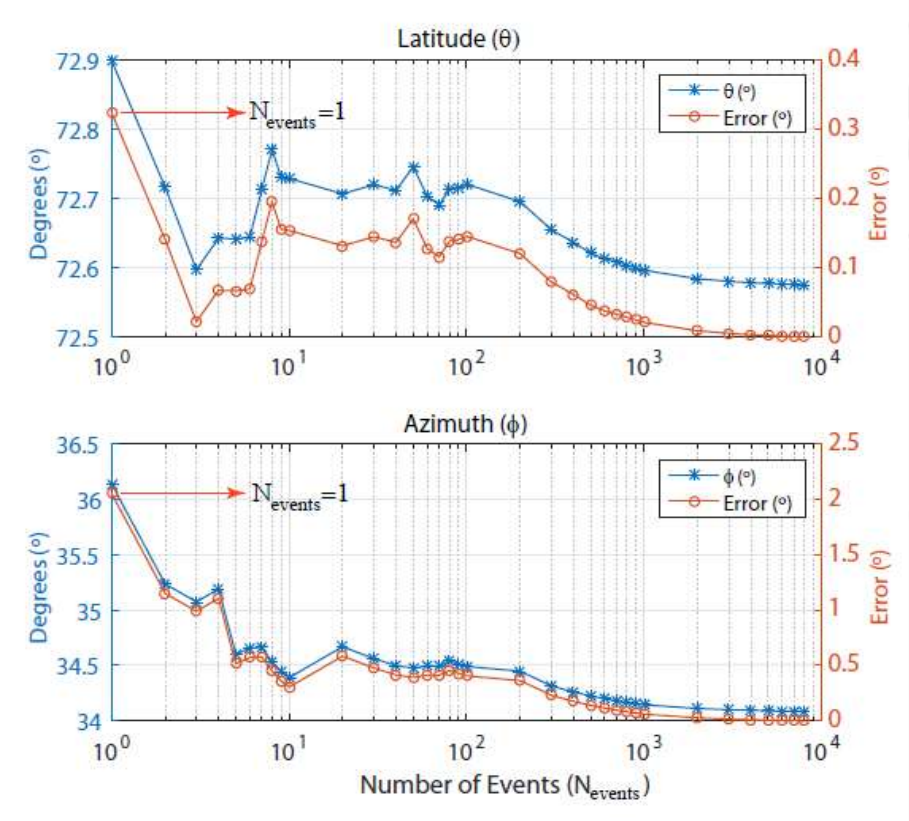
$$\phi = arctan\left(\frac{L\cdot(y-y_c)}{W\cdot(x-x_c)}\right)$$

$$x = \frac{1}{N_{events}}\cdot\sum_{i=1}^{N_{events}} x_i$$

$$y = \frac{1}{N_{events}}\cdot\sum_{j=1}^{N_{events}} y_j$$

Event-based Vision: Optopus Sensor + Pinhole Optics

Time-to-first-spike Operation



- It is posible to resolve the sun position receiving one event.
- Trade-off between the output data flow and error.

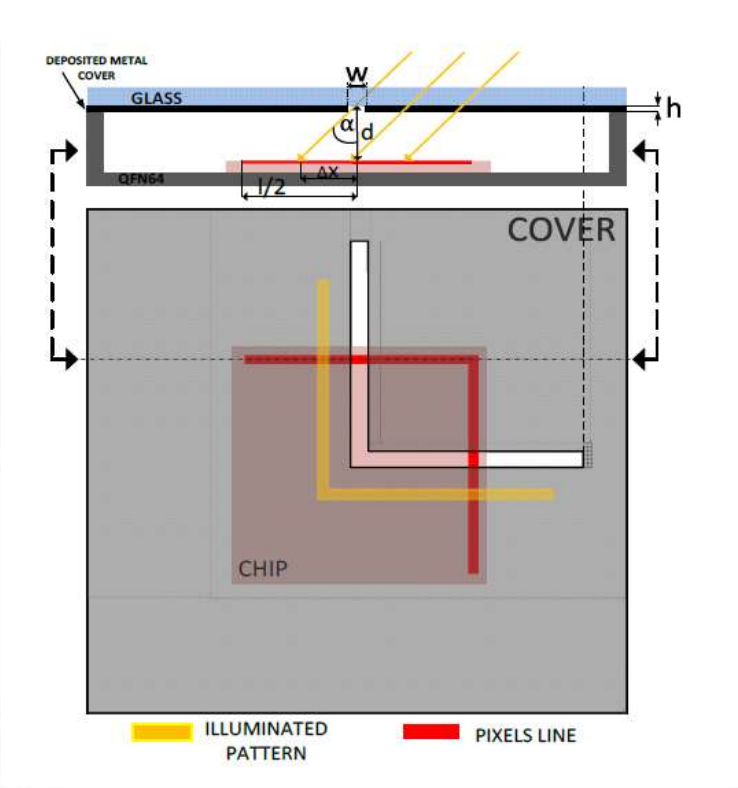
Event-based Vision: Optopus Sensor + Pinhole Optics

Sensor's performance against the art

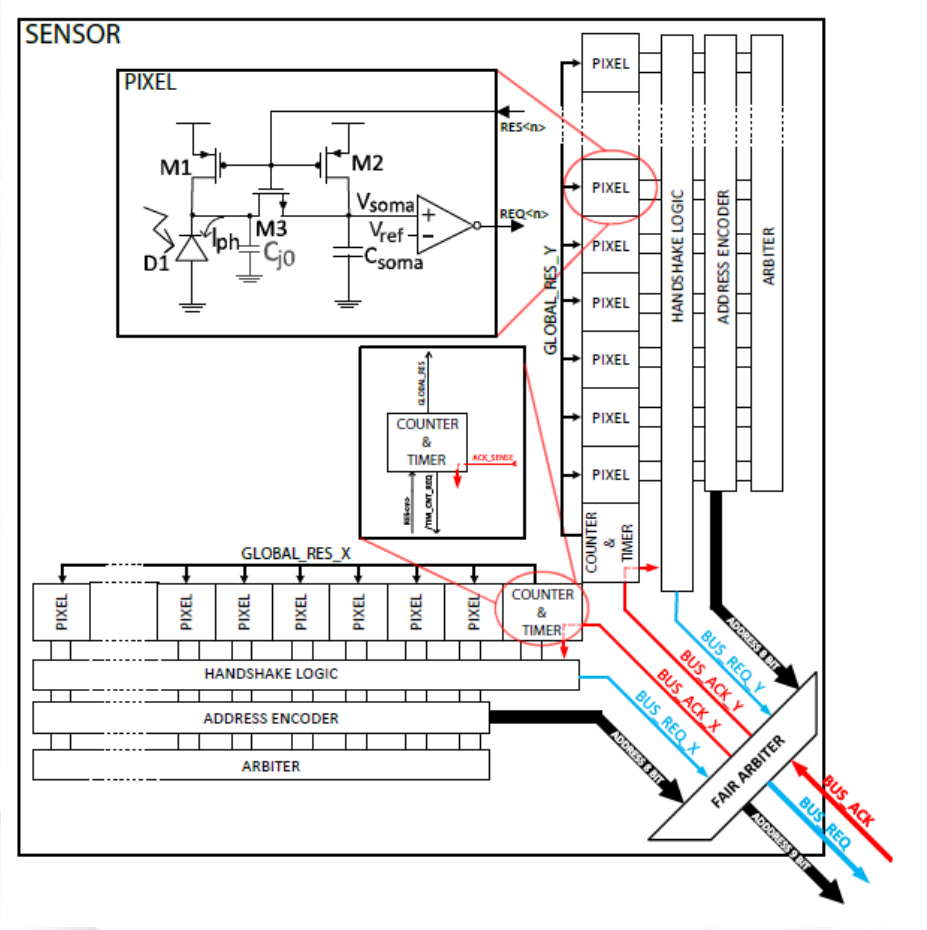
Work	**This Work**	Ning et al. [3]	Galileo ESA [4]	Ortega et al. [1]
Type	Event Based Luminance Sensor	APS Digital Sensor	APS Digital Sensor	Analog Sun Sensor
Operation Principle	TFS	Frame-based	Frame-based	Photocurrent Ratio
Technology	AMS 0.18μm HV	0.18μm 1P4M	UMC 0.18μm	ND
Power Supply	3.3/5V	3.3/1.8V	3.3/1.8V	ND
Chip Dimensions	4120μm× 3315μm	5mm×5mm	11mm×11mm	6.8mm×13.8mm
Number of Pixels	128×96	368×368	512×512	2 pairs of photodiodes
Pixel Pitch	25μm× 25μm	6.5μm×6.5μm	11μm×11μm	NA
FOV	146°	94°	128°	120°
Power Consumption	52mW	42.73mW	520mW	ND
Latency	<5ms@1klux or lower	10frames/s	10frames/s	NA
Dynamic Range	>100dB	52dB	ND	NA
Resolution	0.03°	0.004°	<0.005°	ND
Accuracy	0.0132°(θ), 0.05°(ϕ)	0.01°	0.024°	0.15°
Amount of data	1-100 Events	368 pixels (acquisition mode) +25×25pixels (tracking mode)=945pixels	1 frame (acquisition mode) + ROI (tracking mode)	4 analog voltages to be readout

Event-based Vision: Custom Design

Sensor's lid arrangement

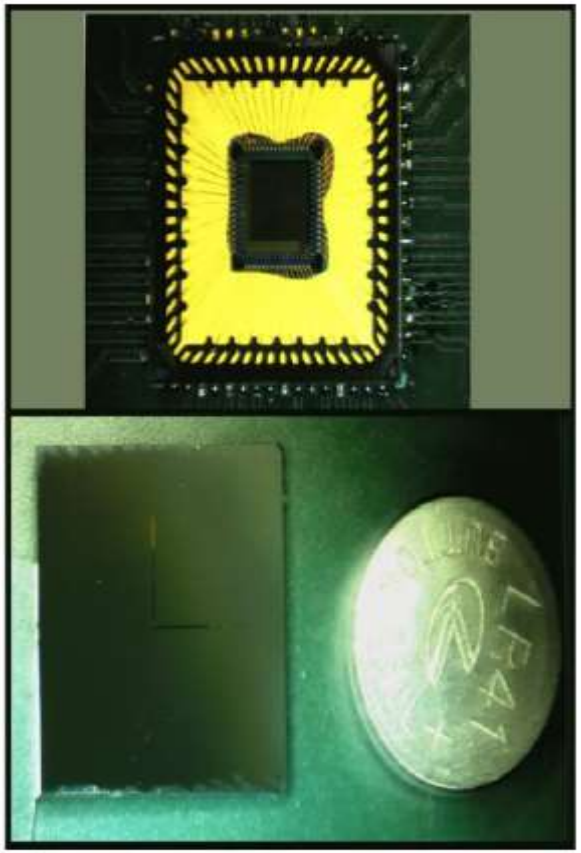


Sensor's block diagram



w=50µm, d=375µm, l=2256µm, h=100nm

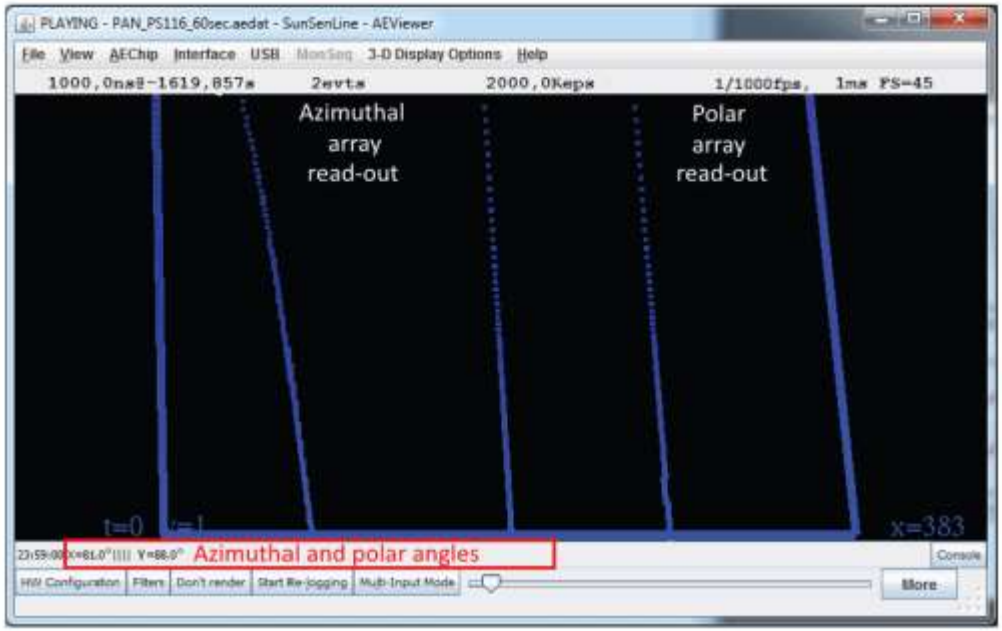
Event-based Vision: Custom Design

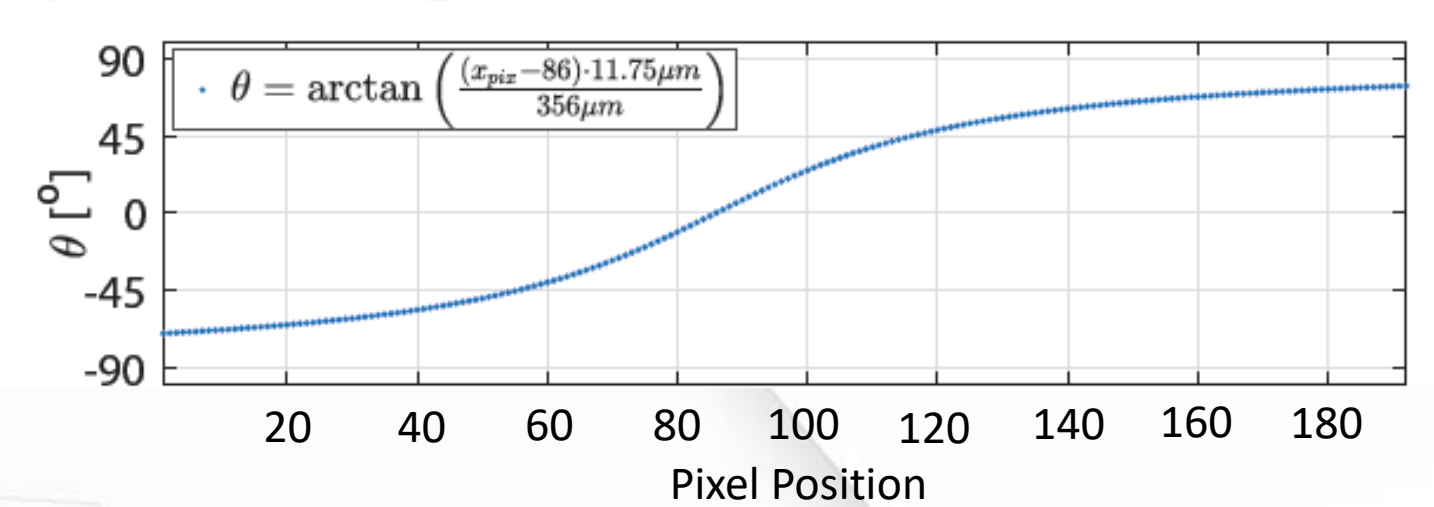


Dimensions: 9.5mmx9.5mmx1mm

Sensor test with real sunlight

Event-based Vision: Custom Design





Event-based Vision: Custom Design

Sensor's performance against the art

	Ortega et al. [8]	Xie et al. [4]	Liebe et al. [16]	This work
Type	Analog Sun Sensor	APS Digital Sensor	APS Digital Sensor	**Event Based Sensor**
Operation Principle	Photodiodes Ratio	Frame-based	Frame-based	**TFnS**
Technology	ND	$0.18\mu m$ 1P4M	$0.5\mu m$ CMOS	**AMS 0.35μm opto (C350)**
Power Supply	ND	$3.3/1.8V$	ND	**3V**
Sensor size	(3 x 3 x 1.2) cm	ND	$4.2cm^3$	**(9.5 x 9.5 x 1) mm**
Sensor Weight	24 grams	ND	11 grams	**0.3 grams**
Pixel array	4 photodiodes	368 x 368	512 x 512	**2 x 192 pixels**
Pixel size	$0.75mm$x$2mm$	$6.5\mu m$ x $6.5\mu m$	$12\mu m$ x $12\mu m$	**9μm x 32μm**
Chip size	$6.8mm$x$13.8mm$	$5mm$x$5mm$	$6.1mm$x$6.1mm$	**2.5mm x 2.5mm (8% of area used)**
FOV	120°	$\pm 47^o$	160°	**144°**
Resolution	ND	0.004^o	ND	**$0.22^o \div 1.88^o$**
Accuracy	0.15^o	ND	$\approx 0.04^o$	**$0.98^o(\theta)$ and $0.42^o(\phi)$.**
Precision	ND	0.01^o	ND	**$0.104^o(\theta)$, $0.061^o(\phi)$**
Latency	ND	10fps	30fps	**88μs (eqiuvalent to 11.3kfps)**
Power consumption	ND	$42.73mW$	$30mW$	**6.3μW**

Event-based Vision: Custom Design

- ✓ **Better resolution.**
- ✓ **Better accuracy**
- ✓ **Less power consumption**

- × Requires precise optic aligment.
- × 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.