Low-power smart imagers for vision-enabled wireless sensor networks and a case study

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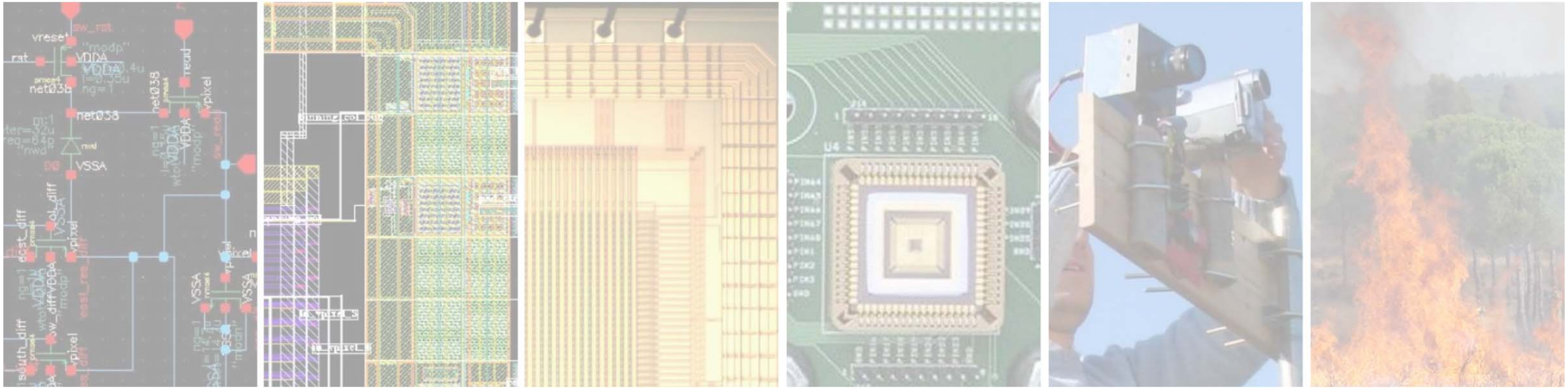


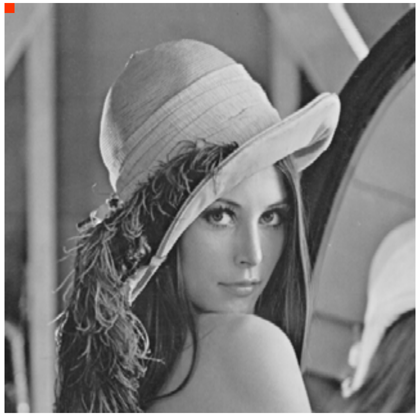
First ACM / IEEE International Workshop On Architecture of Smart Camera

Clermont Ferrand, France April 5-6, 2012

Low-level image processing

↓ INSTRUCTION FLOW, ↑ COMPUTATIONAL LOAD

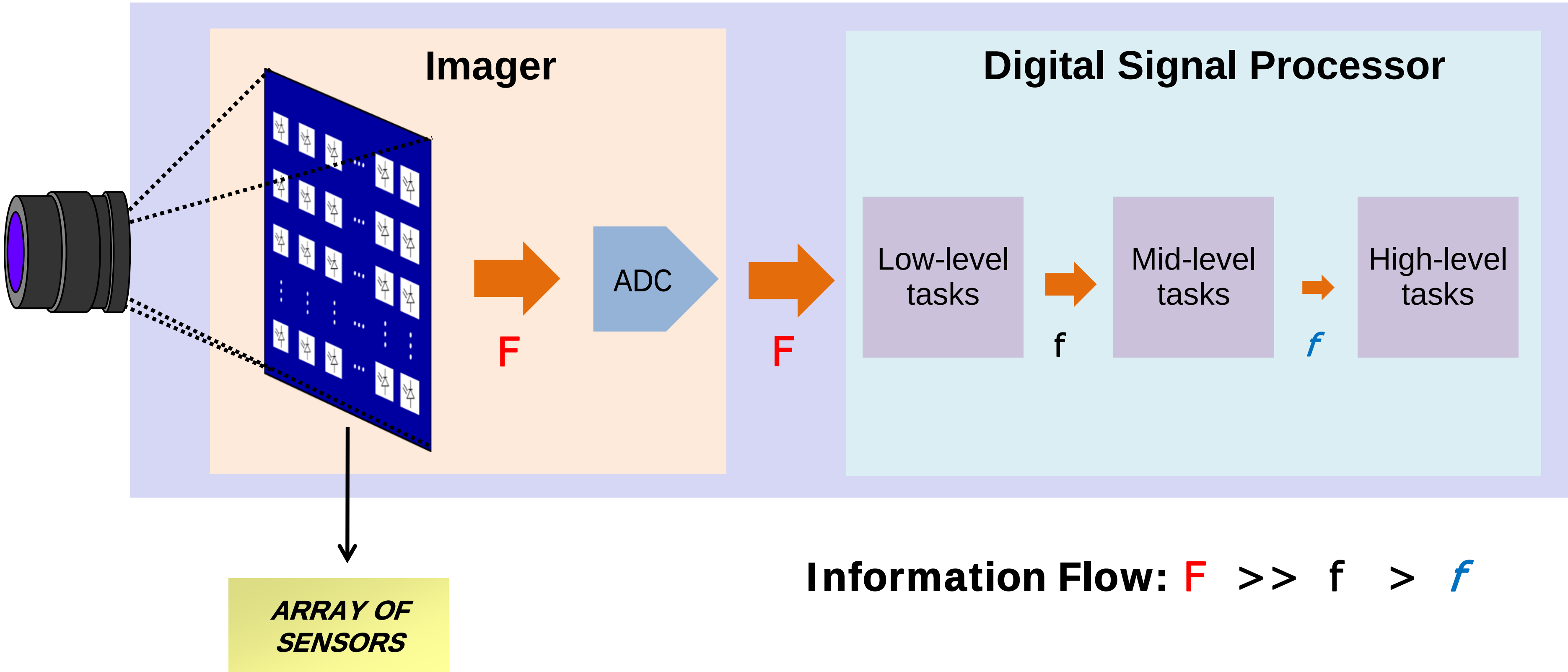
Sobel Operators



- **Potential parallel operation**
- **Moderate accuracy required**

Conventional approach

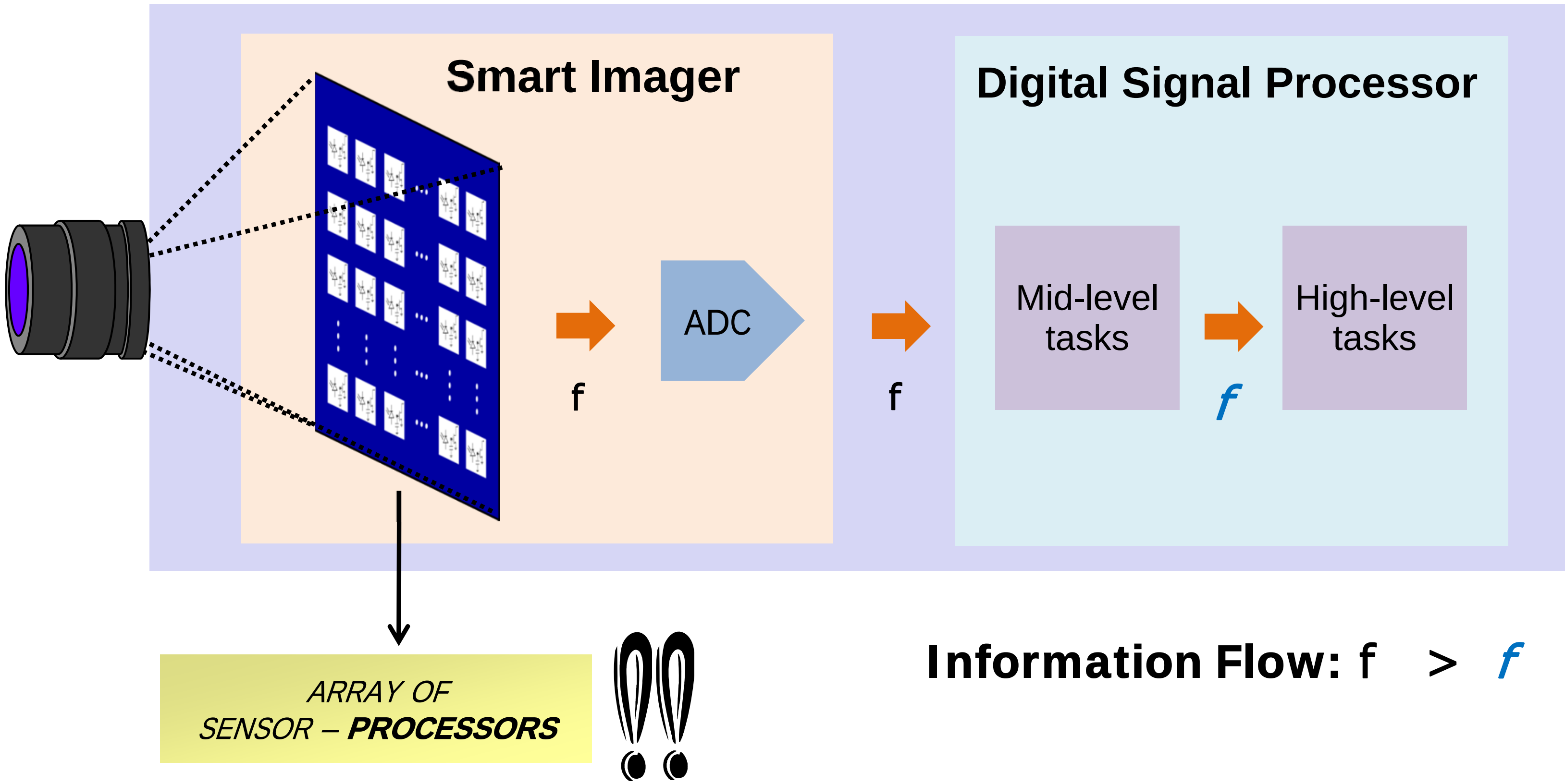
- **Analytic issues are mostly software issues**
  - **Brute force pattern matching used by many system developers**
  - **Extremely inefficient in terms of speed and power**



Information Flow: F >> f > f

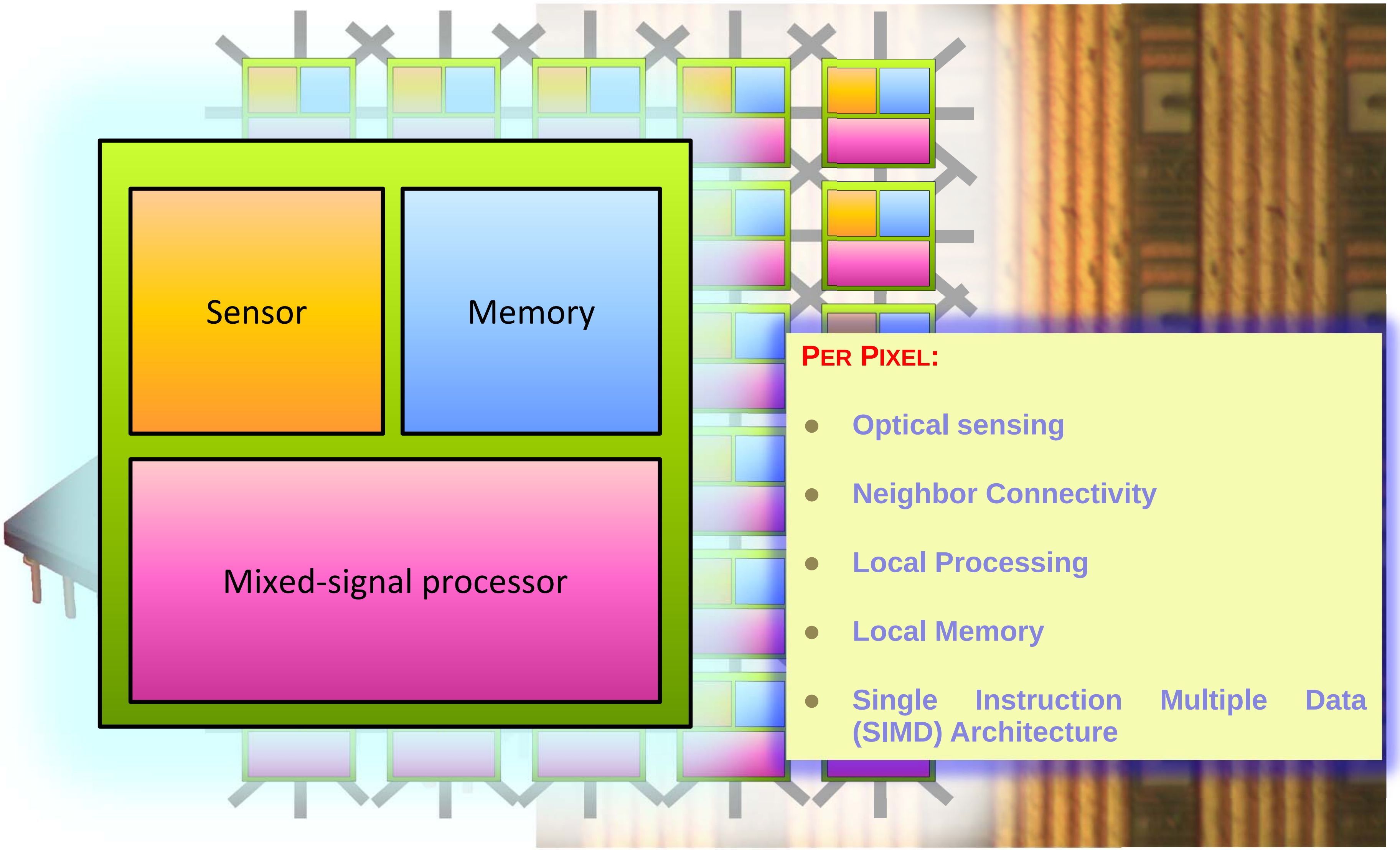
Focal-plane array computing

- **Content-aware sensing-processing**
- **Progressive extraction of relevant information**
- **Parallel and distributed processing**
- **Distributed memory**



Information Flow: f > *f*

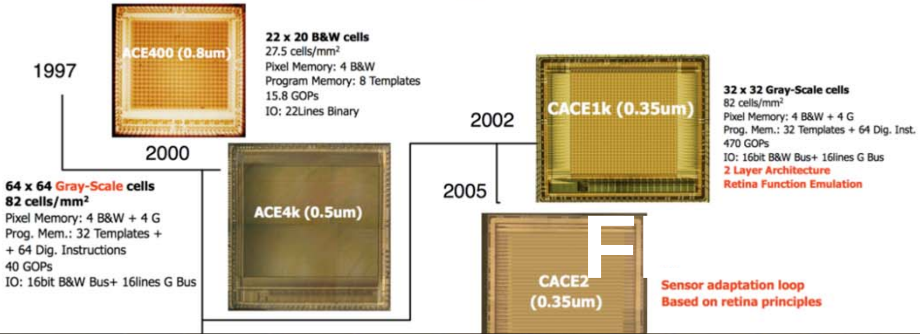
Focal-plane array computing

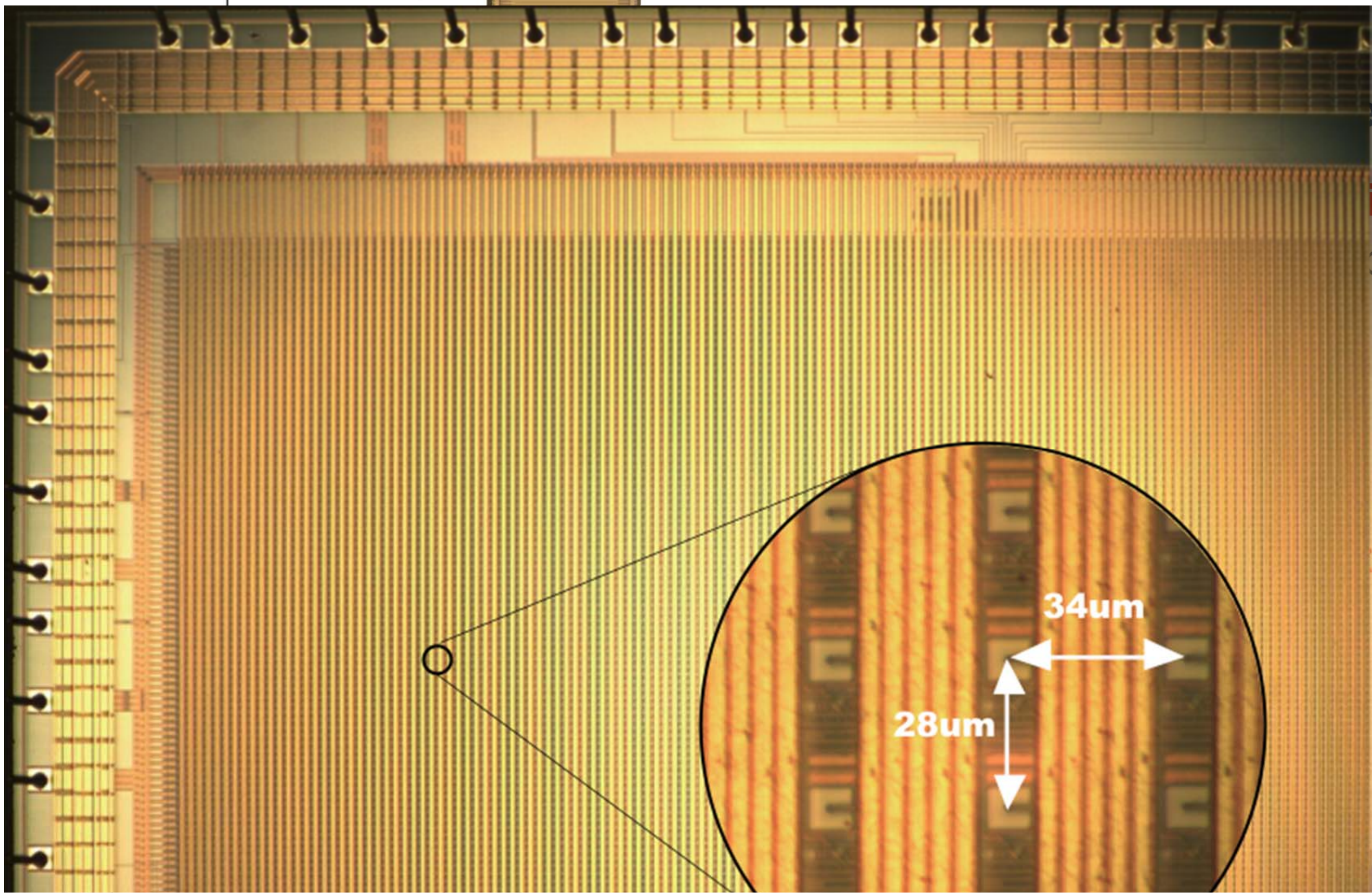


PER PIXEL:

- Optical sensing
- Neighbor Connectivity
- Local Processing
- Local Memory
- Single Instruction Multiple Data (SIMD) Architecture

Focal-plane array computing

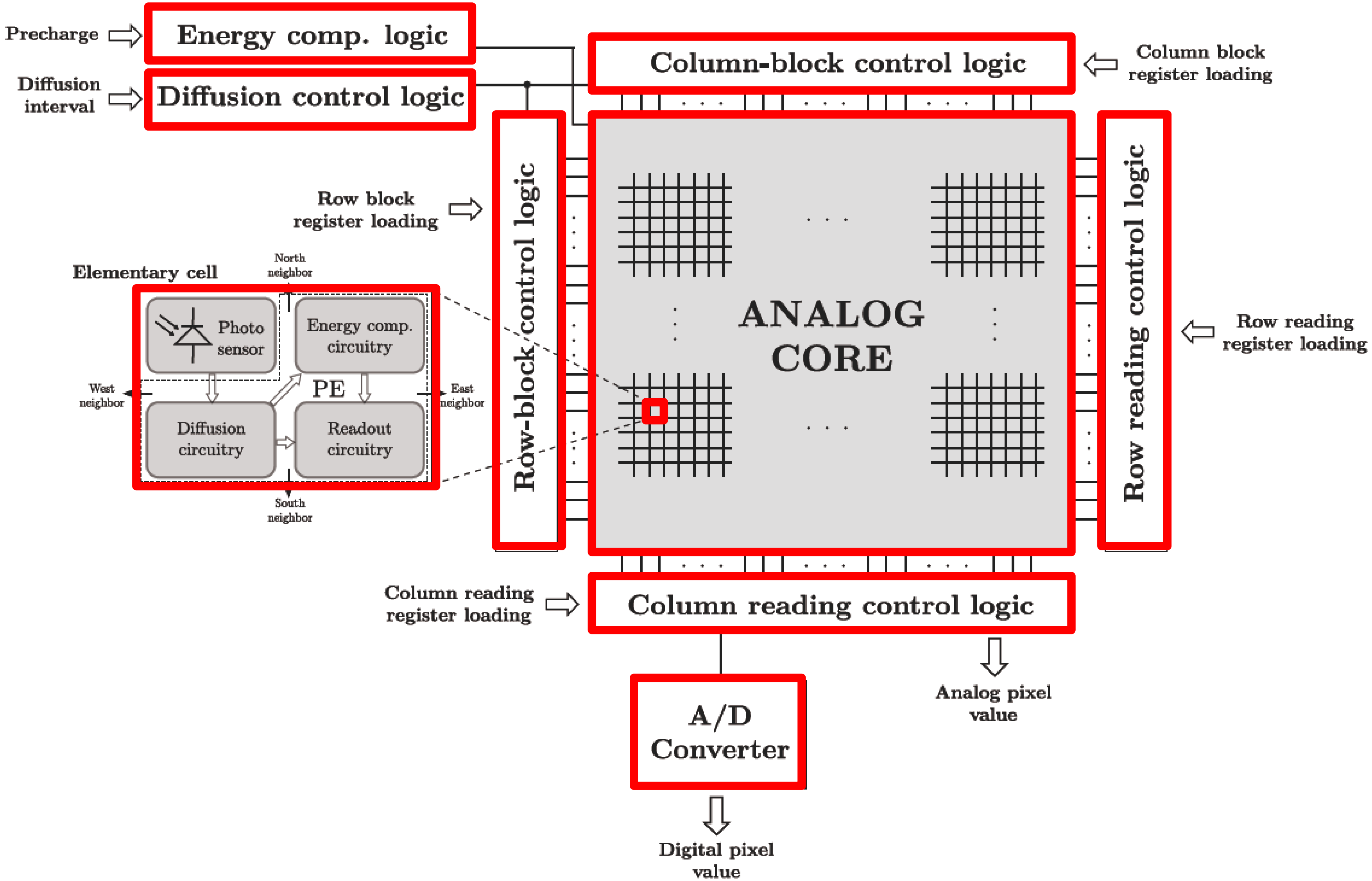




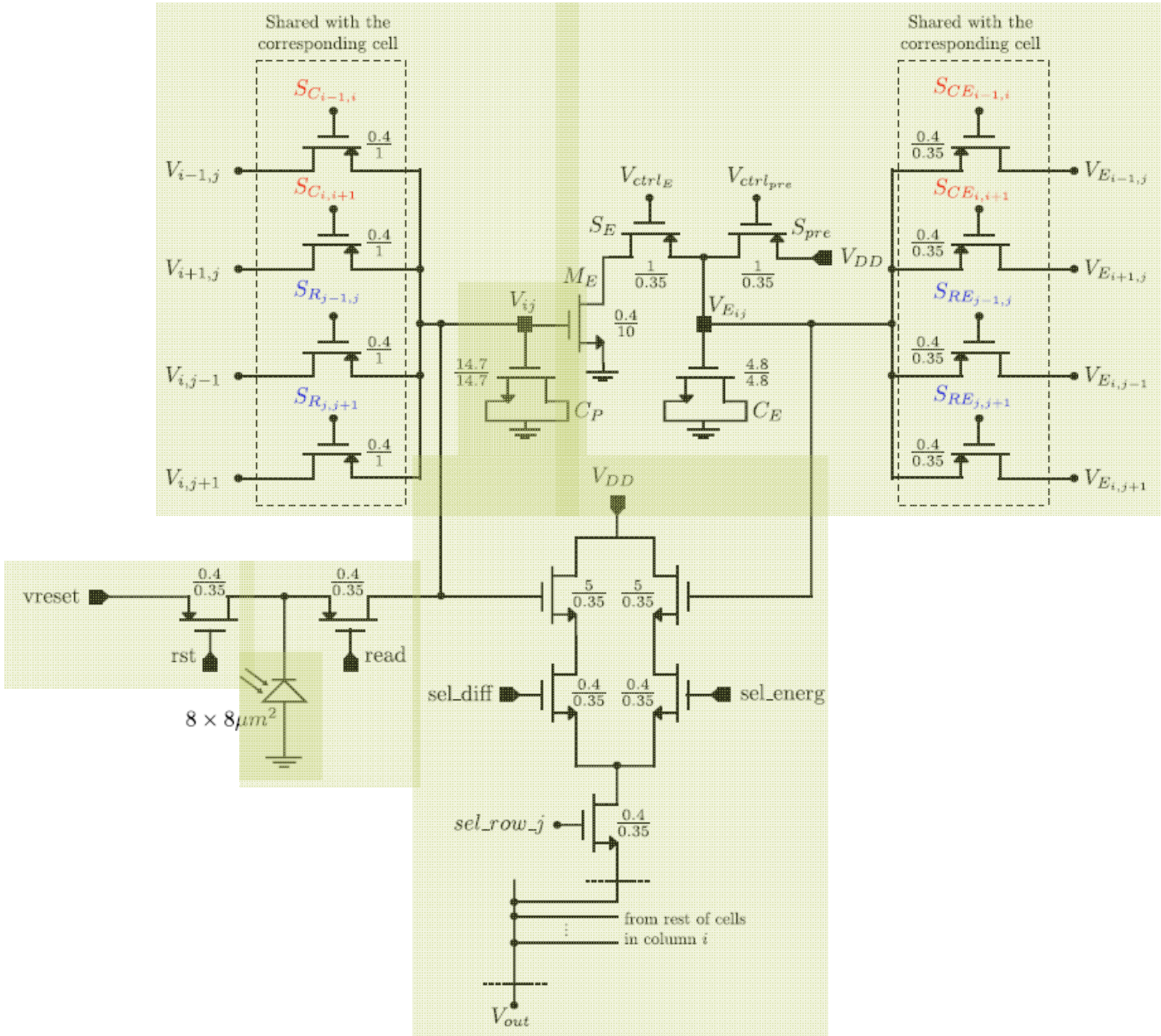
- Several generation of chips designed
- With fully programmable features
- large variety of ...ts
- ...ion at >1,000F/s ...pixel
- ...l filtering with
- HDR acquisition ...ra-frame DR

FLIP-Q: floorplan

J. Fernández Berni, R. Carmona Galán and L. Carranza González, "FLIP-Q: A QCIF Resolution Focal-Plane Array for Low-Power Image Processing," in *IEEE J. Solid-State Circuits, vol. 46, no. 3, pp. 669–680, March 2011*

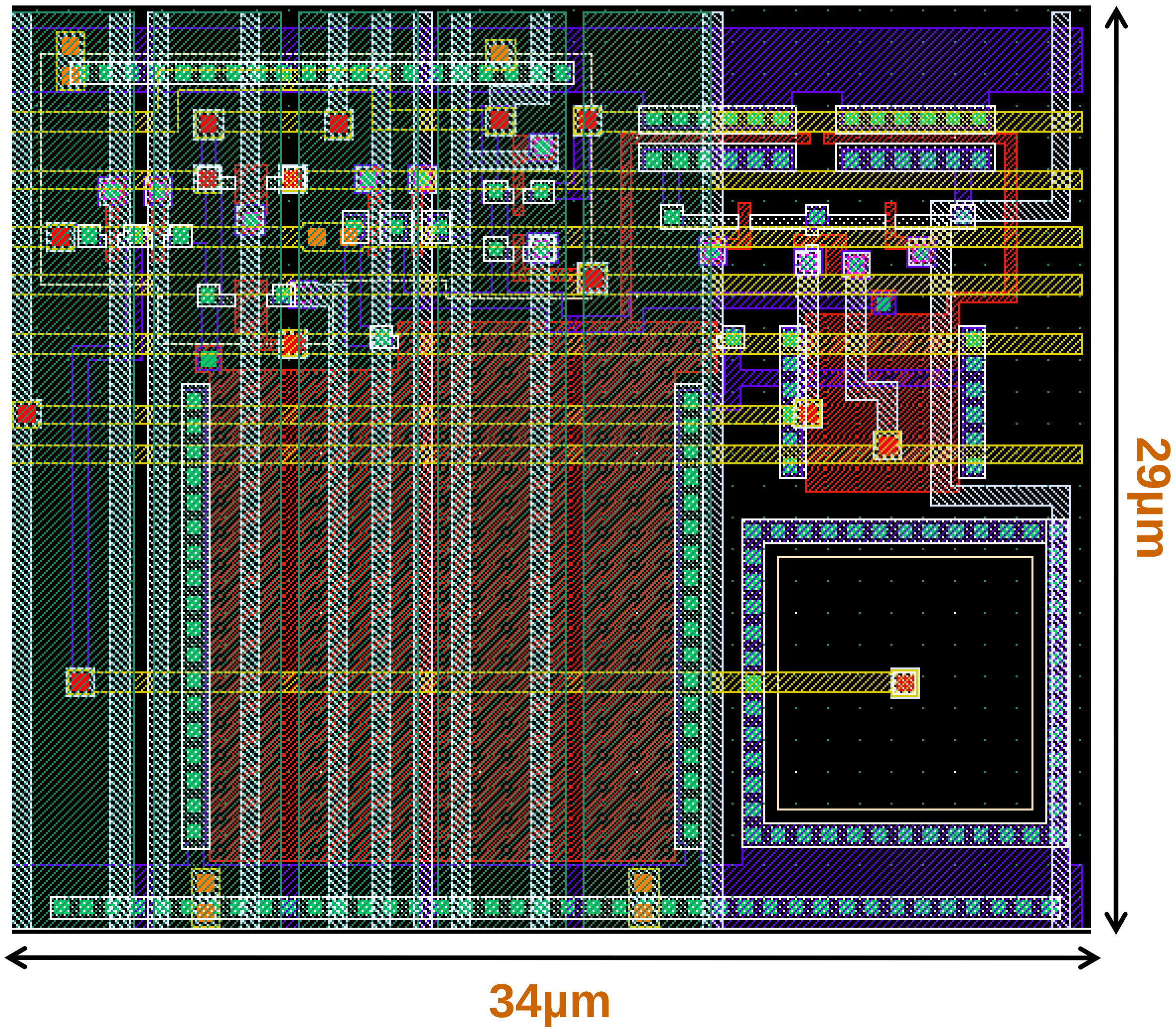


FLIP-Q: elementary processing cell



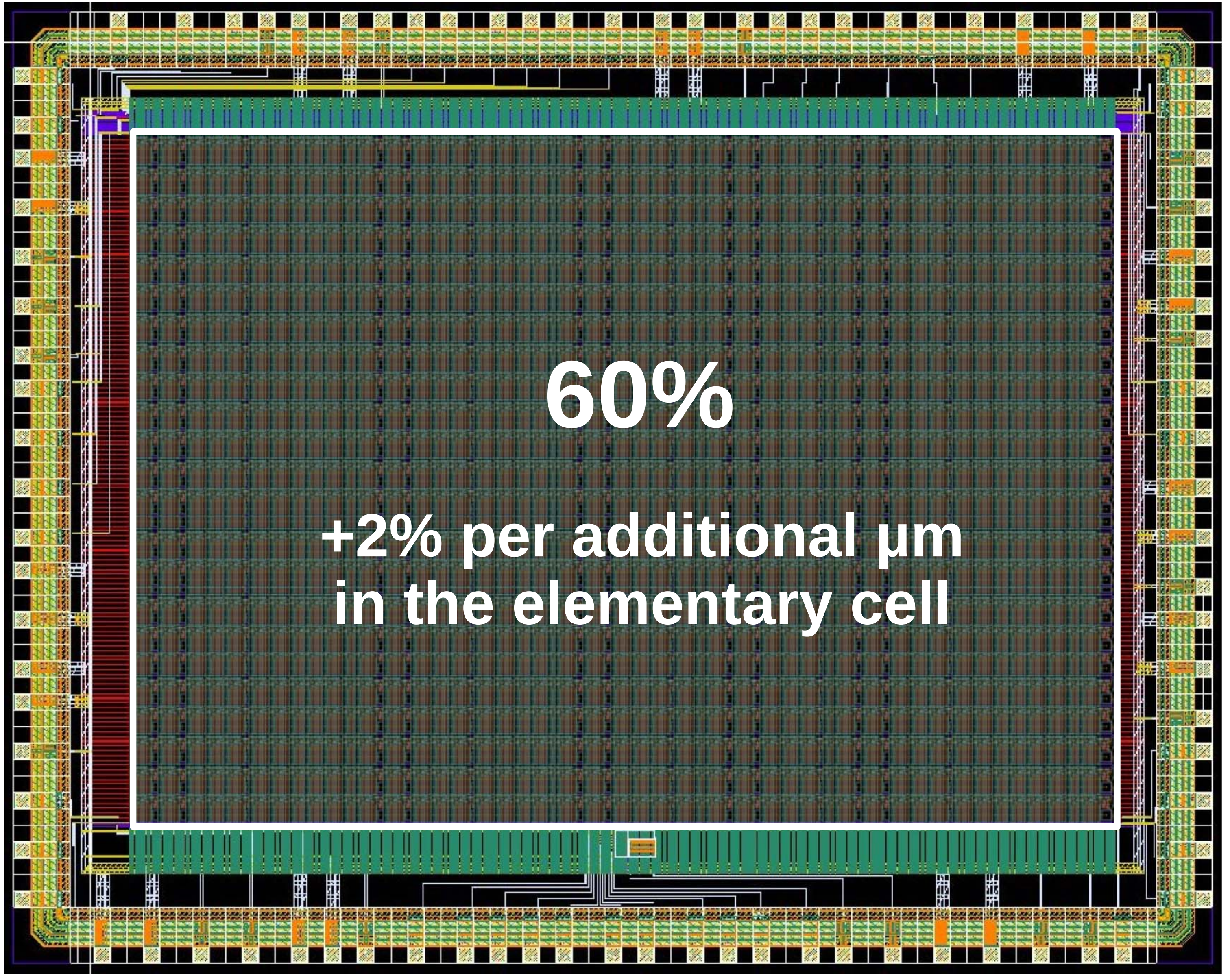
- **Reset** transistor
- n-well/p-substrate **photodiode**
- Electronic **global shutter**
- Programmable **block-wise** image **filtering** and **averaging**
- Programmable **block-wise** image **energy** computation
- **Readout** circuitry

Physical design

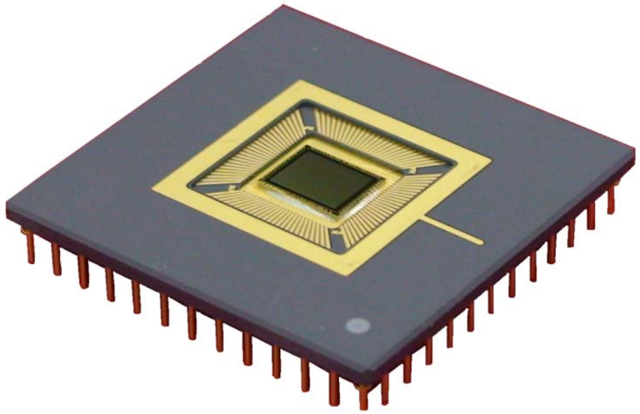


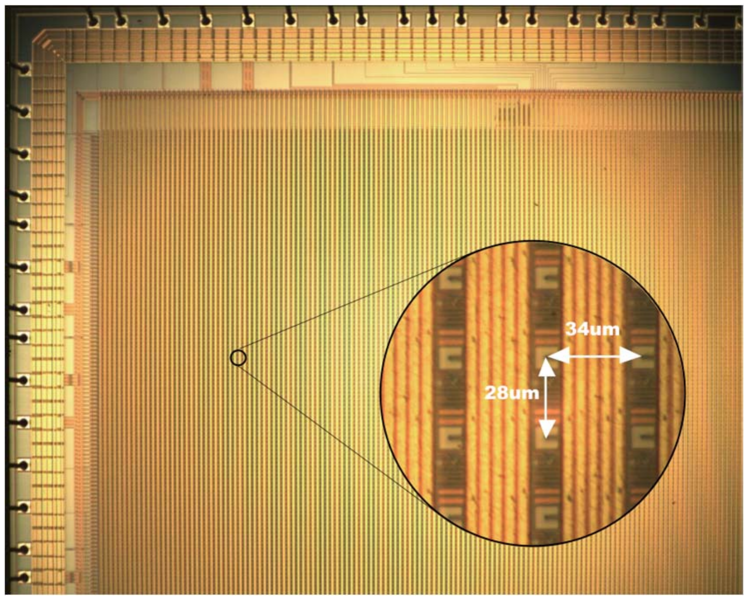
- **Crucial aspect affecting the total area, the fill factor and the pixel pitch**
- **The electrical design must be realized bearing in mind the subsequent physical design**
- **Relevant issues:**
  - **Metal layers available**
  - **Full-custom routing**
  - **Make the most of the design rules**

Physical design



FLIP-Q: A prototype smart imager

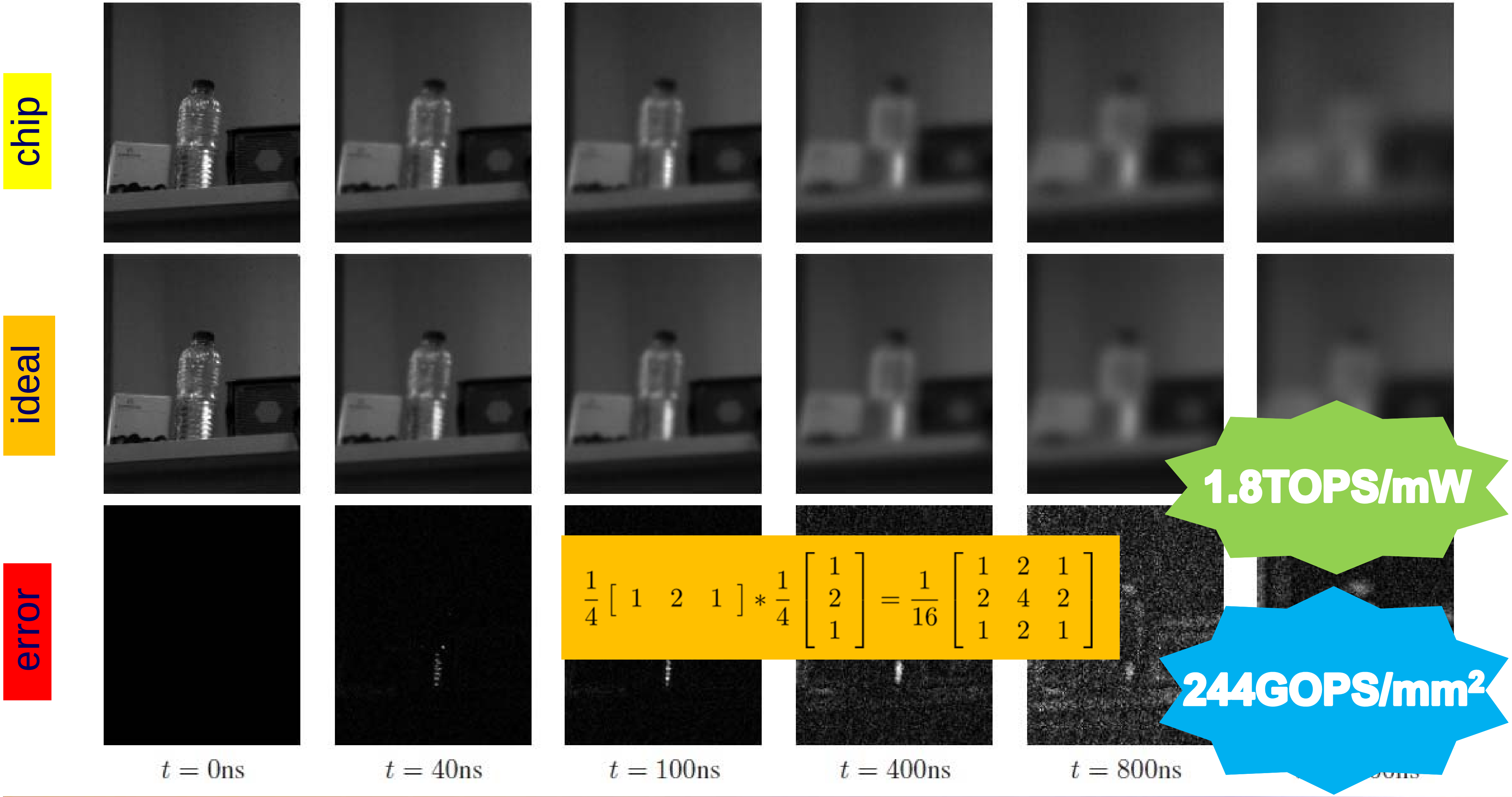




Technology	0.35μm CMOS 2P4M
Vendor (Process)	Austria Microsystems (C35OPTO)
Die size (with pads)	7280.8μm $\times$ 5780.8μm
Cell size	34.07μm $\times$ 29.13μm
Fill factor	6.45%
Resolution	QCIF: 176$\times$144 px
Photodiode type	n-well/p-substrate
Power supply	3.3V
Signal range	[1.5V,2.5V]
FPN	0.72%
PRNU (50% signal range)	2.42%
Sensitivity	0.15V/(lux·s)
Measured power consumption (worst case)	5.6mW@30fps 22 $\times$ 18px
Predicted power consumption (worst case)	17.6mW@30fps 176 $\times$ 144px
ADC throughput	0.11MSa/s (9μs/Sa)
Internal clock freq. range	0.5-150MHz

FLIP-Q: on-chip early vision

Programmable Gaussian filtering



$$\frac{1}{4}\begin{bmatrix} 1 & 2 & 1 \end{bmatrix} * \frac{1}{4}\begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} = \frac{1}{16}\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

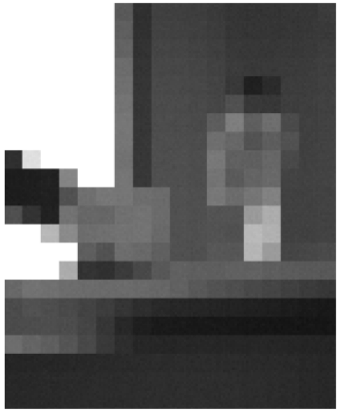
FLIP-Q: on-chip early vision

Fully-programmable multi-resolution scene representation

On-chip images

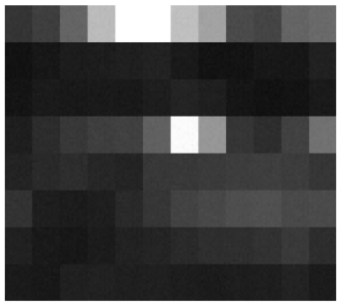
Original image

4×4 px



8×8 px

Original image



12×16 px

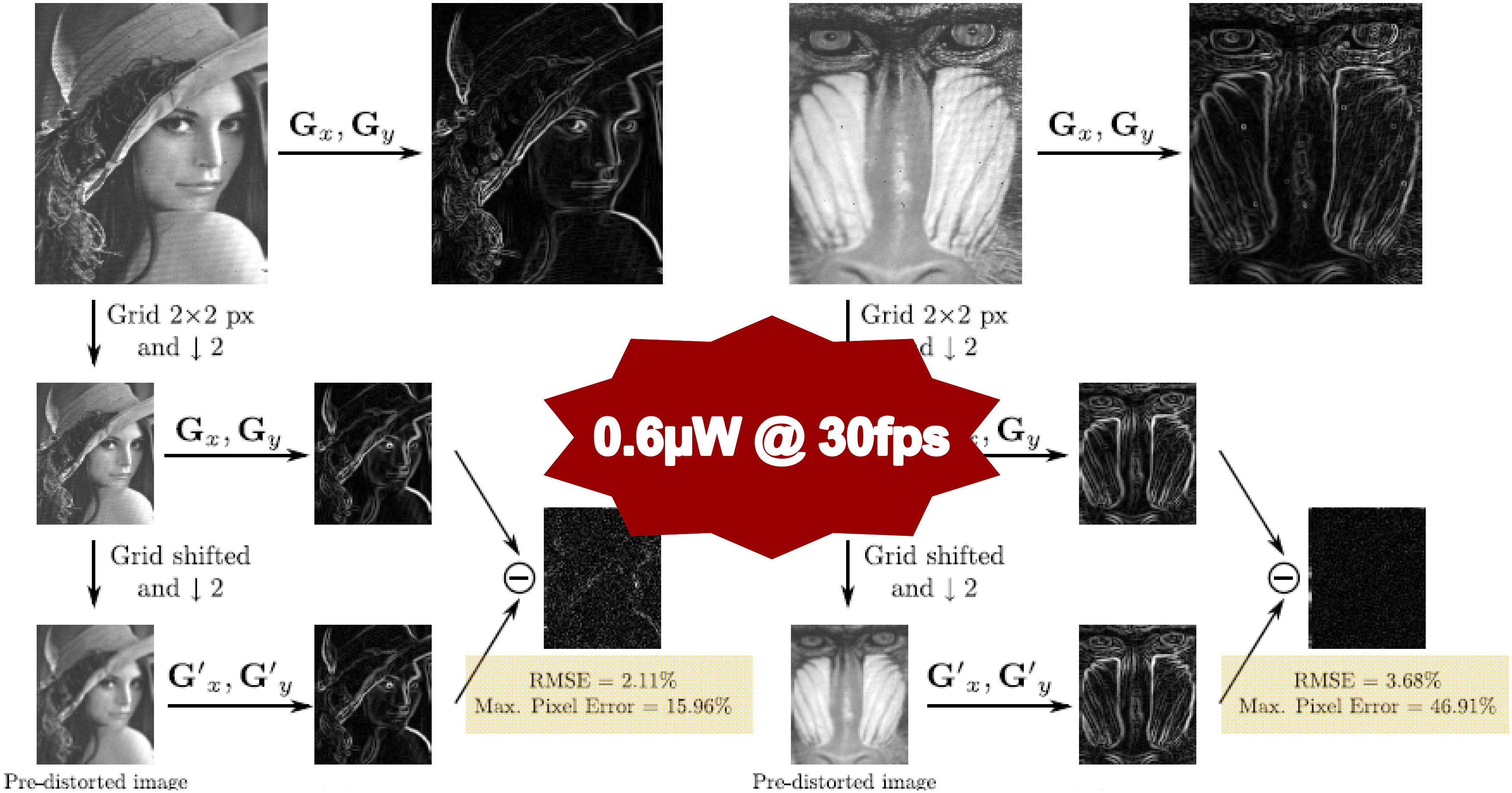
Foveation

No extra time

No extra energy

FLIP-Q: on-chip early vision

Image pre-distortion for reduced kernel filtering



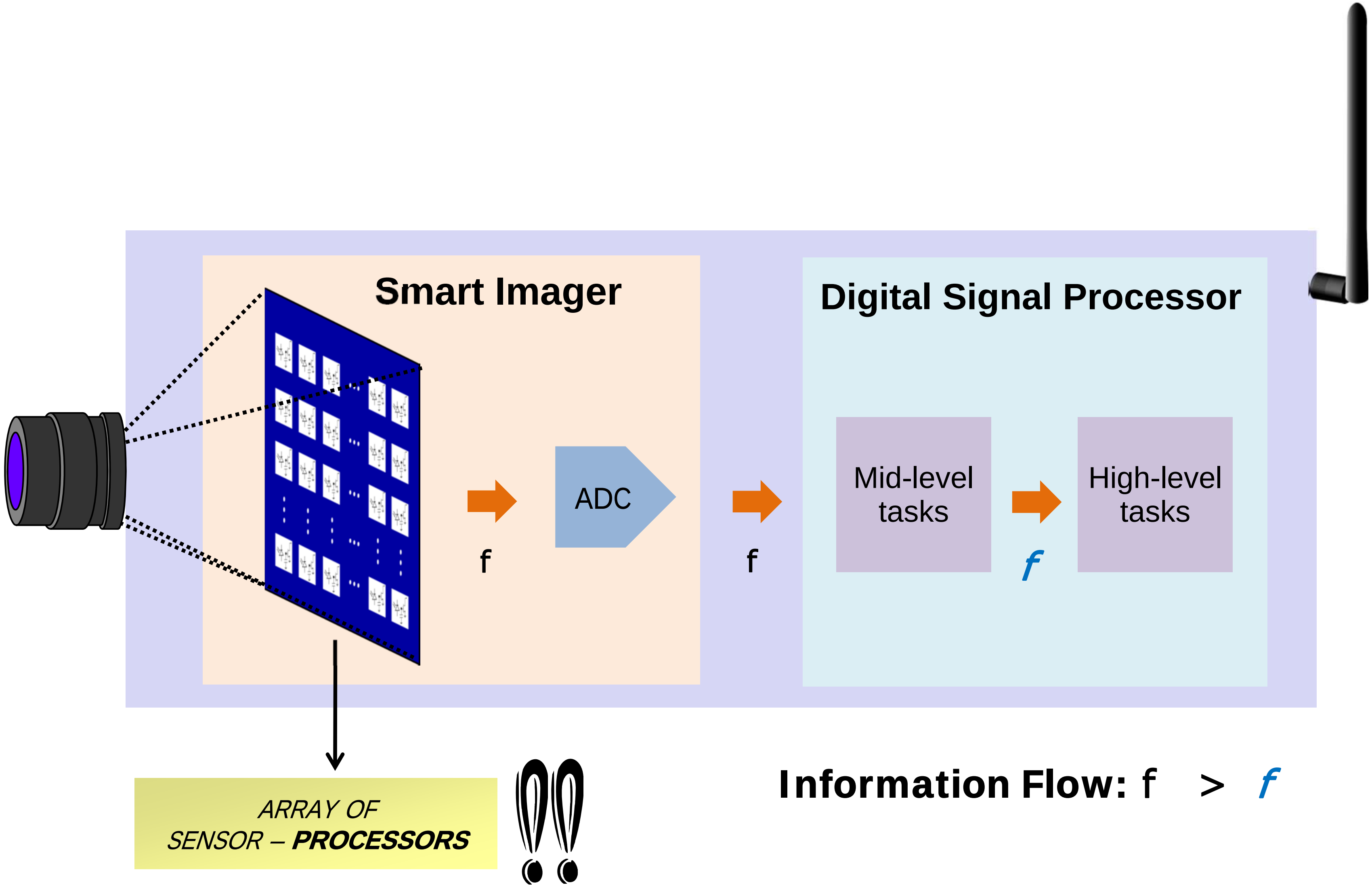
Original kernels

$$G_x = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix} \quad G_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}$$

Reduced kernels

$$G'_x = 4\begin{bmatrix} 1 & -1 \\ 1 & -1 \end{bmatrix} \quad G'_y = 4\begin{bmatrix} 1 & 1 \\ -1 & -1 \end{bmatrix}$$

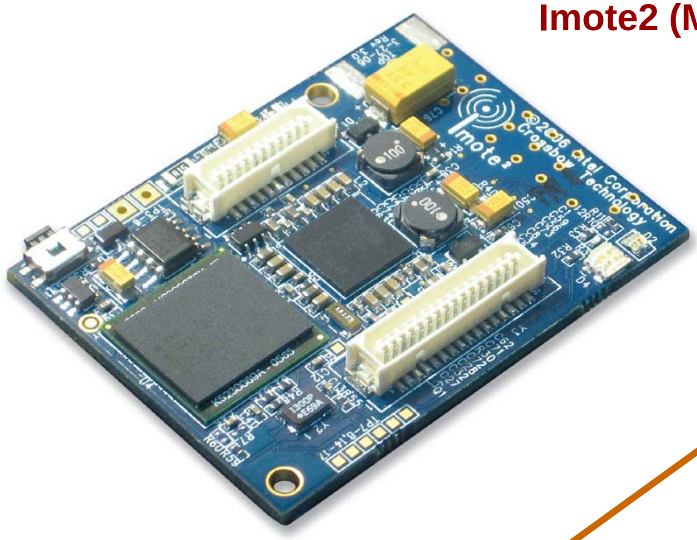
Wi-FLIP: a vision-enabled WSN node



Information Flow: f > *f*

Wi-FLIP: a vision-enabled WSN node

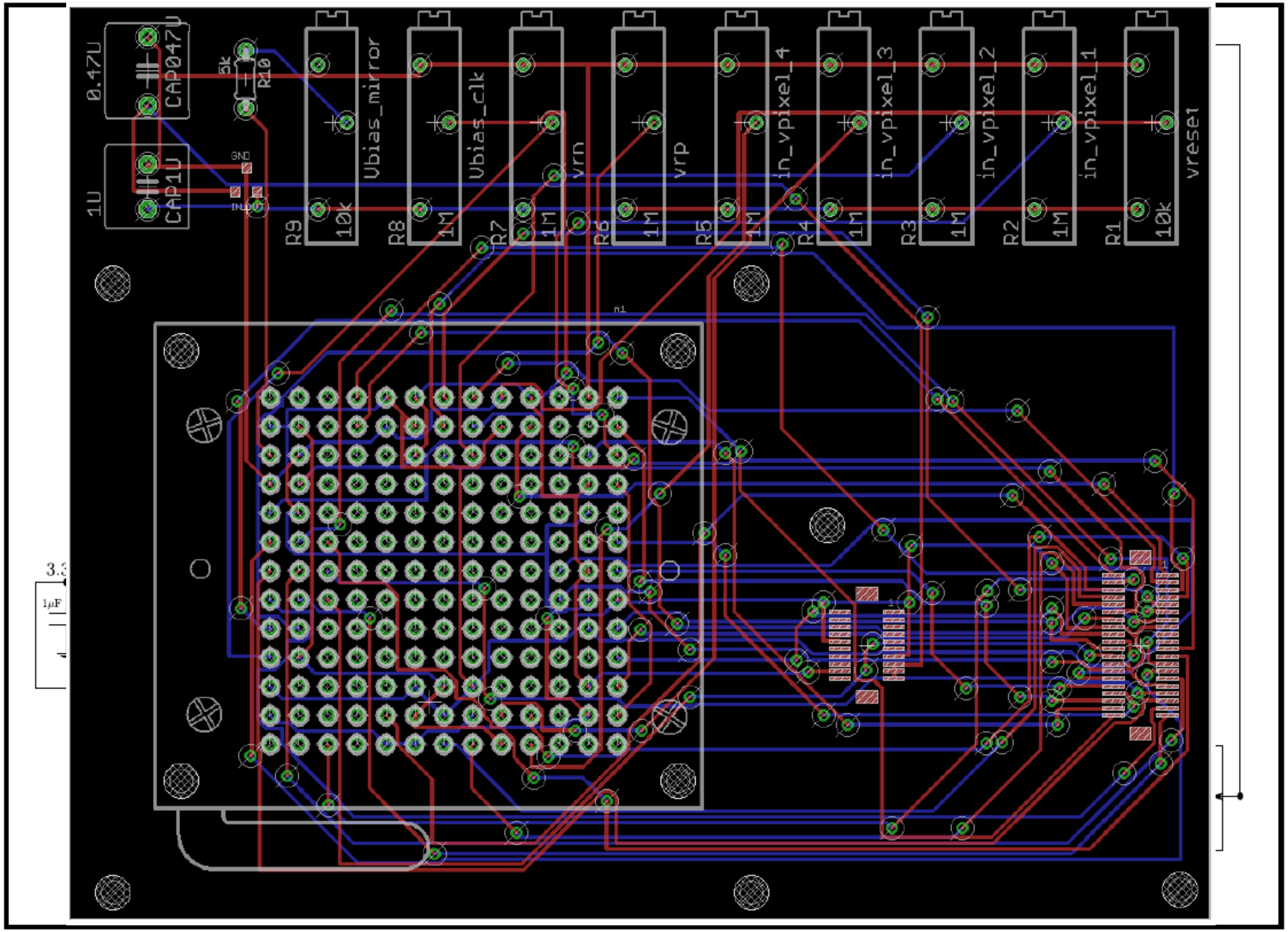
Imote2 (MEMSIC Inc.)



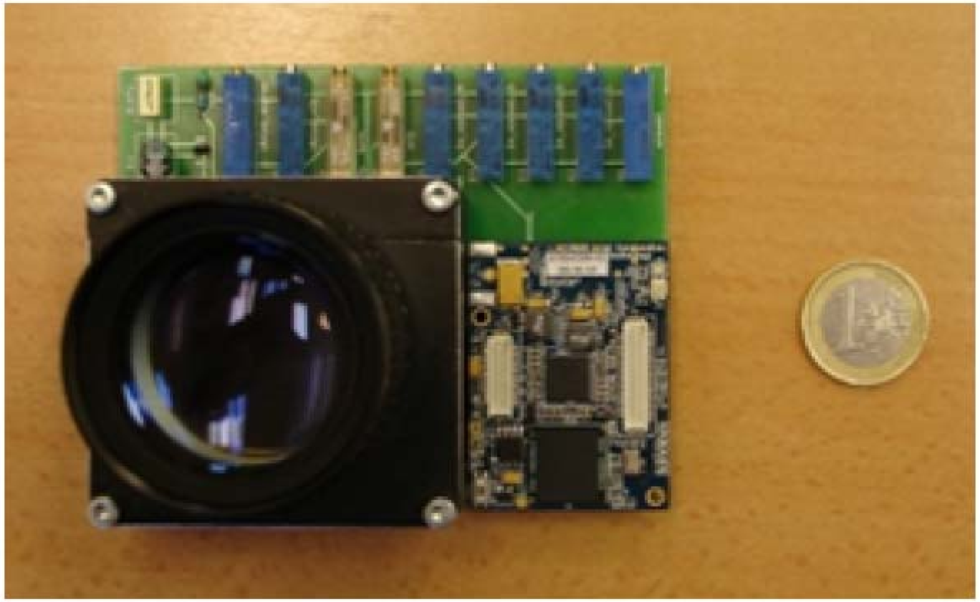
FLIP-Q: 1.7mA for worst case

Processor/Radio Board	IPR2400	Remarks
CPU		
Processor	Marvell PXA271	
SRAM Memory	256 kB	
SDRAM Memory	32MB	
FLASH Memory	32MB	
POWER CONSUMPTION		
Current Draw In Deep Sleep Mode	390 µA	
Current Draw In Active Mode	31 mA	13MHz, radio off
Current Draw In Active Mode	44 mA	13MHz, radio Tx/Rx
Current Draw In Active Mode	66 mA	104MHz, radio Tx/Rx
Radio		
Transceiver	TI CC2420	
Frequency Band (ISM)	2400.0 – 2483.5 MHz	
Data Rate	250 kb/s	
Tx Power	-24 – 0 dBm	
Rx Sensitivity	-94 dBm	
Range (line of sight)	~30 m	With integrated antenna
I/O		
USB Client (mini-B), USB Host		
UART 3x, GPIOs, I^2C, SDI0, SPI 2x, I^2S, AC97, Camera		
Power		
Battery Board	3x AAA	
USB Voltage	5.0 V	
Battery Voltage	3.2 – 4.5 V	
Li-Lon Battery Charger		
Mechanical		
Dimensions Imote2 Board	36mm x 48mm x 9mm	
Weight	12g	

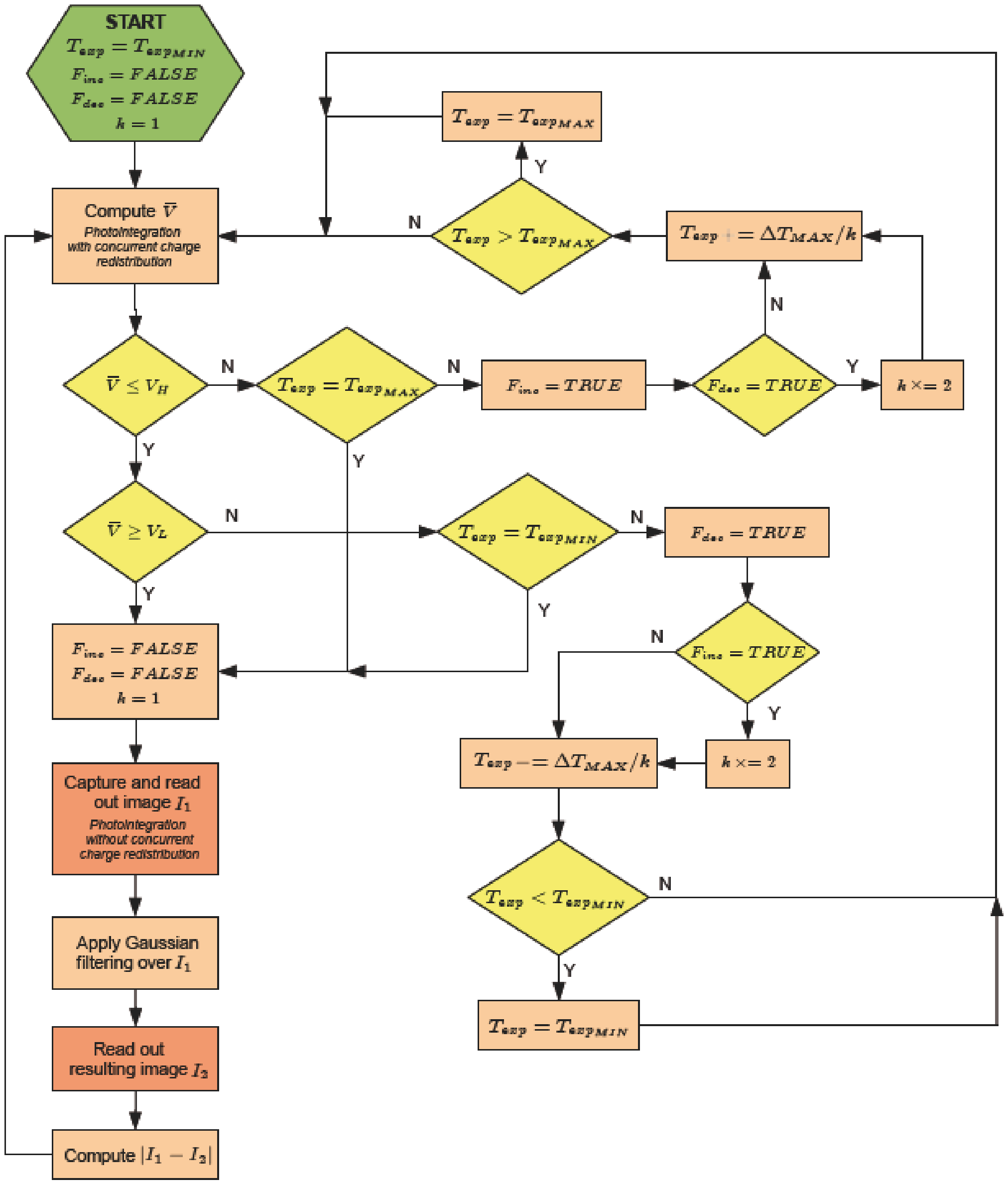
Wi-FLIP: a vision-enabled WSN node



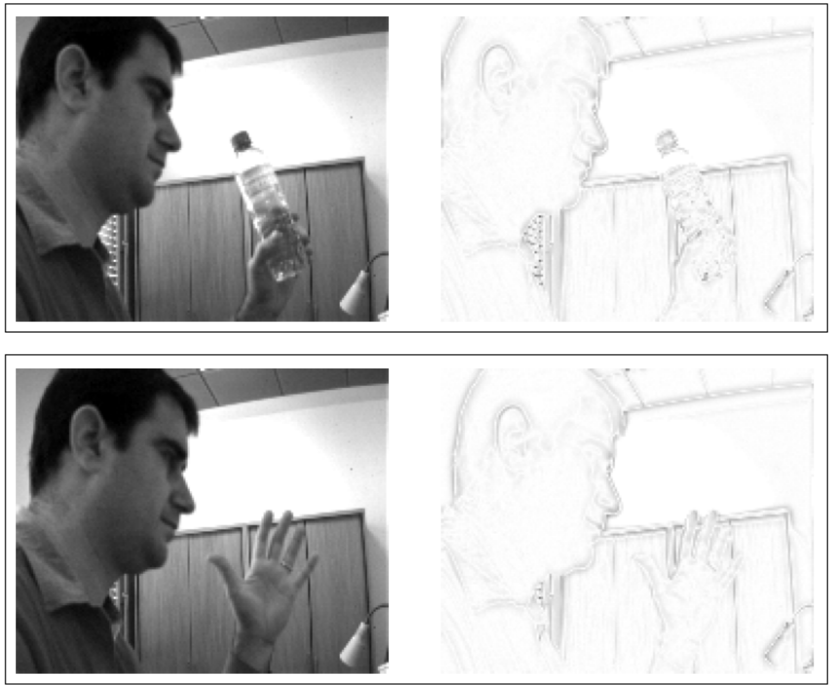
Wi-FLIP: a vision-enabled WSN node



Wi-FLIP: a vision-enabled WSN node



DoG-based edge detection



Wi-FLIP: a vision-enabled WSN node

Resolution (px)	Clock frequency (MHz)	Frame rate	Power consumption (mA)
Full 176×144	13	0.01	38.8
	104	0.05	67.8
	208	0.08	107.8
	416	0.1	155.6
Half 88×72	13	0.04	38.7
	104	0.15	67.1
	208	0.22	105.7
	416	0.25	153.3
Quarter 44×36	13	0.12	38.1
	104	0.41	67.5
	208	0.55	105.9
	416	0.59	153.1

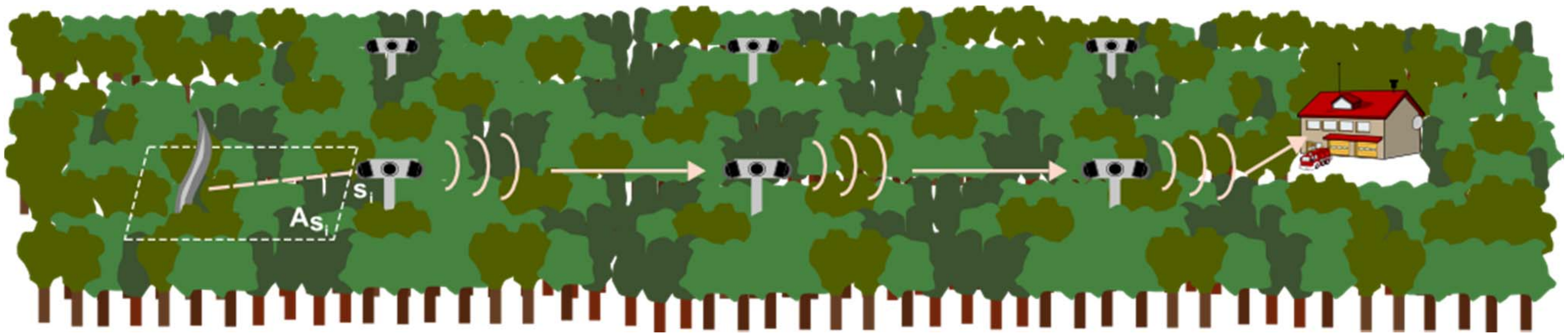
Very low throughput due to slow GPIO ports and TinyOS latency

Case study: early detection of forest fires

- **High** economic **cost**
- Short **maintenance** cycles
- **Coarse grain** coverage
- **Exact** location must be inferred

Case study: early detection of forest fires

- **Vision-enabled Wireless Sensor Network**



ADVANTAGES

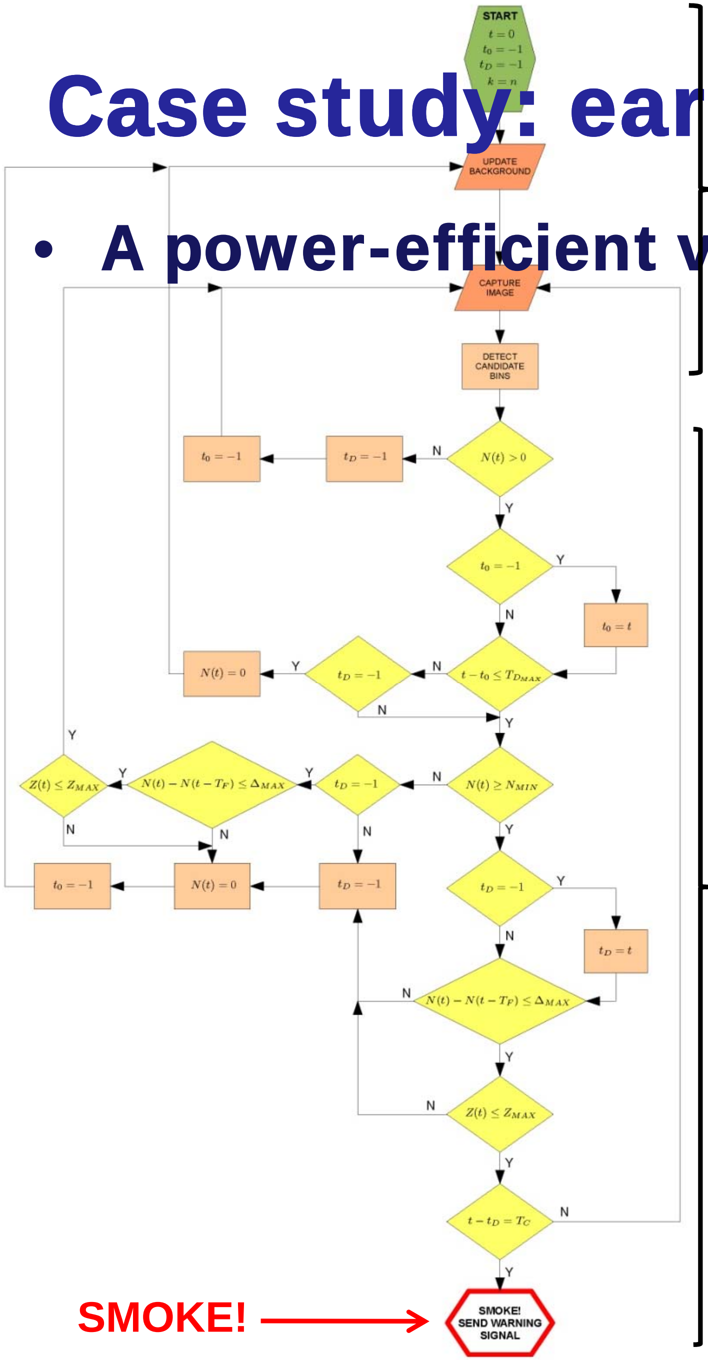
✓ Robustness
✓ Scalability
✓ Reliability
✓ Better temporal resolution
✓ Simpler smoke location

DRAWBACKS

❖ Ultra low power consumption required

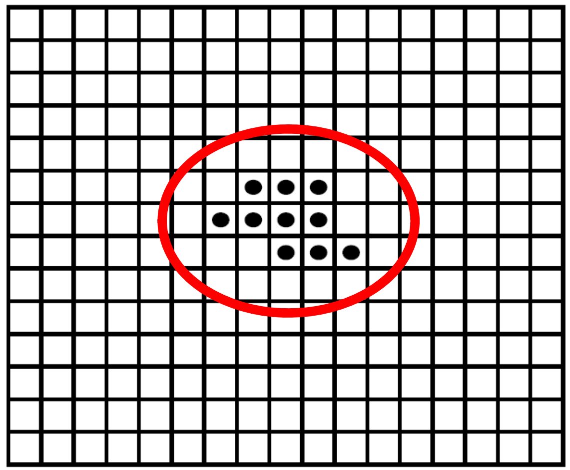
Case study: early d

- A power-efficient vision



SMOKE!

- Reconfigurable focal plane
- Multiresolution scene representation

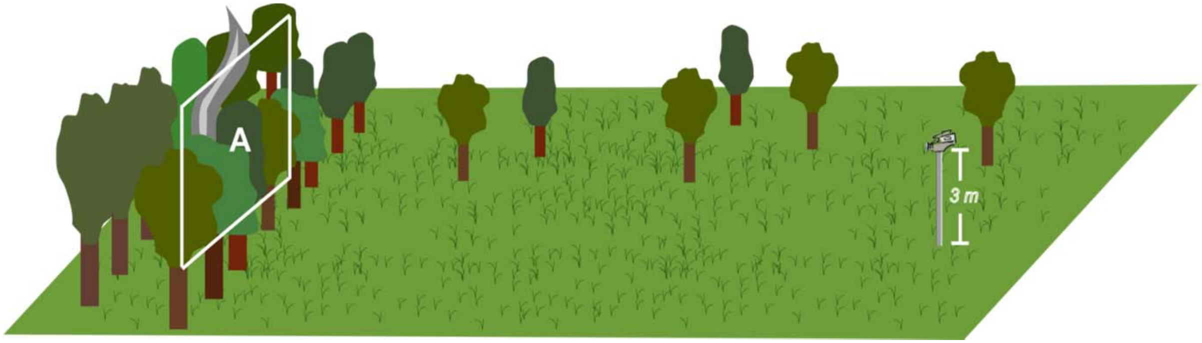


Candidate regions

- Clustering ratio
- Growth rate
- Propagation speed

Case study: early detection of forest fires

- **Preliminary field tests**



Parameter	Value
T_F	$1s$
T_B	$300s$
$W \times H$	15×12px
q	10%
N_{MIN}	14

Parameter	Value
$T_{D_{MAX}}$	$20s$
T_C	$4s$
Δ_{MAX}	30
Z_{MAX}	6

http://www.imse-cnm.csic.es/vmote/

Original sequence

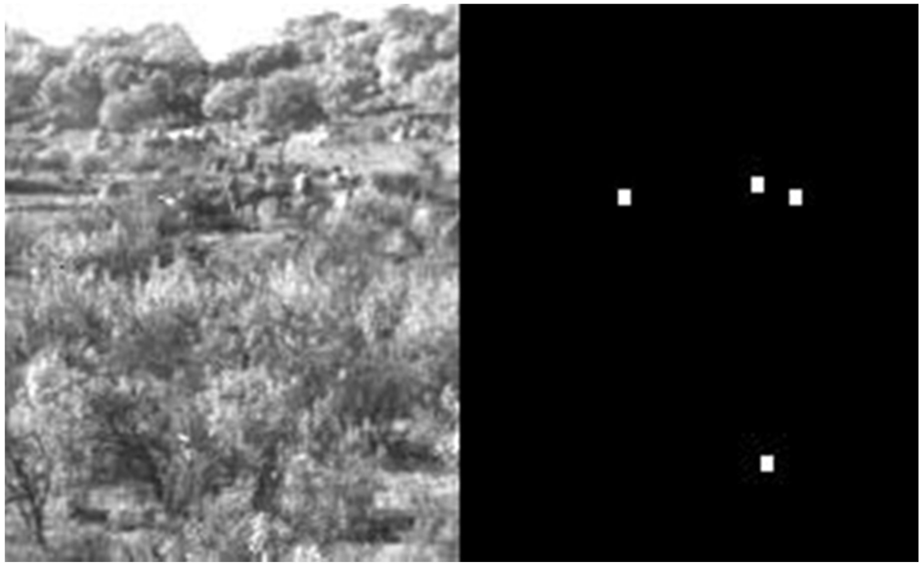
Motion detector

Our algorithm

Case study: early detection of forest fires

- **On-site smoke detection with *Eye-RIS* v1.2**






Case study: early detection of forest fires

- **Field tests with Wi-FLIP**

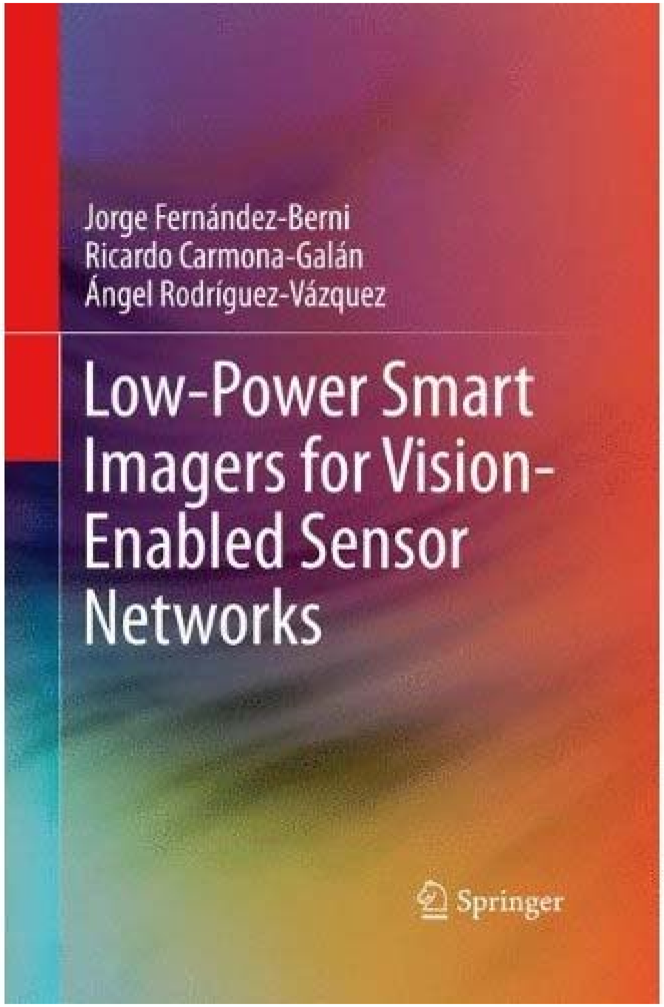
Case study: early detection of forest fires

- **Prescribed burning of a 95m x 20m shrub plot**

- **Wi-FLIP** monitored all the activity for over **two hours**
- **No false** alarm triggered
- **Successful smoke detection** for two of the three vegetation areas explored
- **Thin smoke** generated from a very **sparse** vegetation area was not detected

CONCLUSIONS

- **Early vision** tasks represent a considerably **heavy** computational **load**.
- SIMD-based **massively parallel mixed-signal** processing takes advantage of their intrinsic characteristics to achieve **high power efficiency** and **computational power**.
- **FLIP-Q**: A **prototype** vision chip tailored for **ultra low-power** applications. Very competitive in the state of the art.
- **Wi-FLIP**: A **vision-enabled** Wireless Sensor Network node supported by **Imote2**. Current drawback: low throughput.
- Case study: **Early detection** of **forest fires**, with very good results in terms of **reliability**.



Publication Date: May 31, 2012

Thank you very much for your attention

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Acknowledgments

This work is financially supported by Andalusian Regional Government, through project 2006-TIC-2352, the Spanish Ministry of Economy and Competitiveness, through projects TEC 2009-11812 and IPT-2011-1625-430000, both co-funded by the EU-ERDF and by the Office of Naval Research (USA), through grant N000141110312.

MINISTERIO DE CIENCIA E INNOVACIÓN

Project Part-Financed by the European Union

European Regional Development Fund