Sense Lab

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FEI: Fusion Processing of Sensing Energy and Information for Self-Sustainable Infrared Smart Vision System

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Asia South Pacific Design Automation Conference 2025 (ASP-DAC2025)
Innovative Techniques for Energy-Efficient and Reliable Hardware Systems Session

Outline

- Background
- **FEI: F**usion processing of sensing **E**nergy and **I**nformation
- The **IPC^2** System
- **IPC$_p$**: **I**nformation **P**ower **C**oupler
- **IPC$_{trl}$**: **I**ntelligent **P**ower **C**ontroller
- Simulation Results
- Conclusion

Background

- Infrared smart vision systems are increasingly prevalent in the era of the Internet of Things.
  - Widely deployed on the edge
  - Always-on working
  - Sense the ambient environment
  - Perform low-complexity but frequent tasks

Security Monitoring[1]

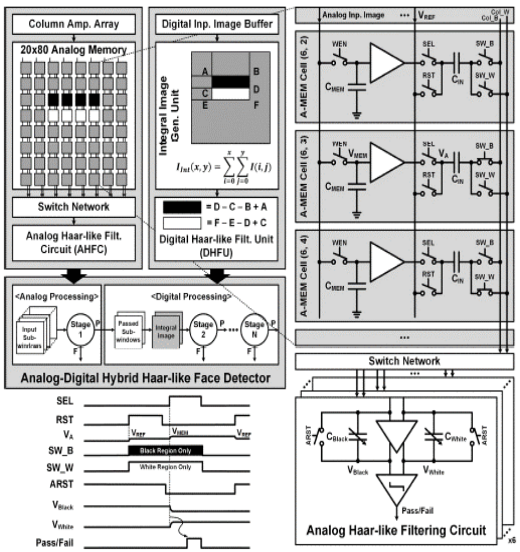
Unmanned Aerial Vehicle Navigation[2]

Human Behavior Target Tracking[3]

- **Significant power consumption.**
- **Power-limited batteries bring huge cost to device maintenance.**

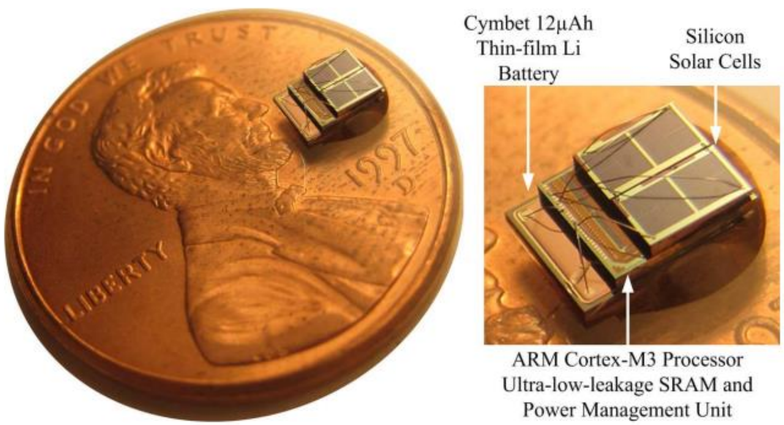
Background

- Advanced low power processing architectures



Ultra-low-power always-on face detector[4]

- Efficient energy harvesting methods to eliminate batteries



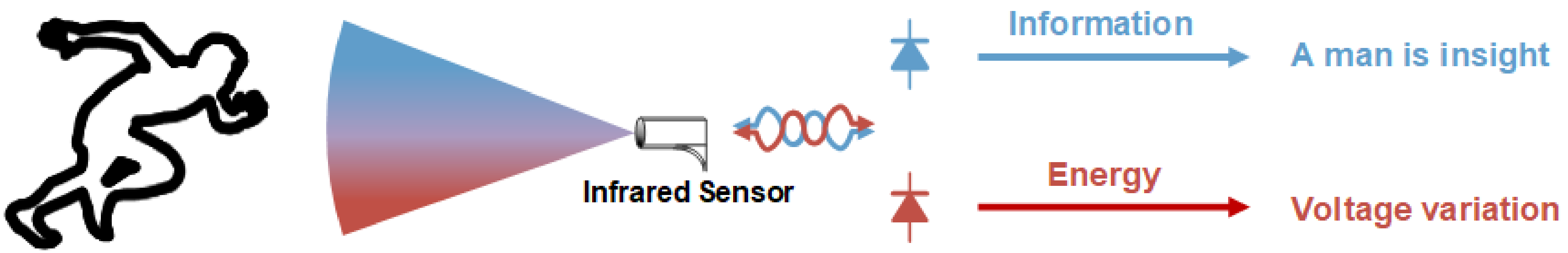
Energy-Autonomous Sensor System[5]

- **Energy and Information are processed Separately**
  - **Lower power consumption**
  - **Higher energy efficiency**
  - **Deeper integration**

Fusion

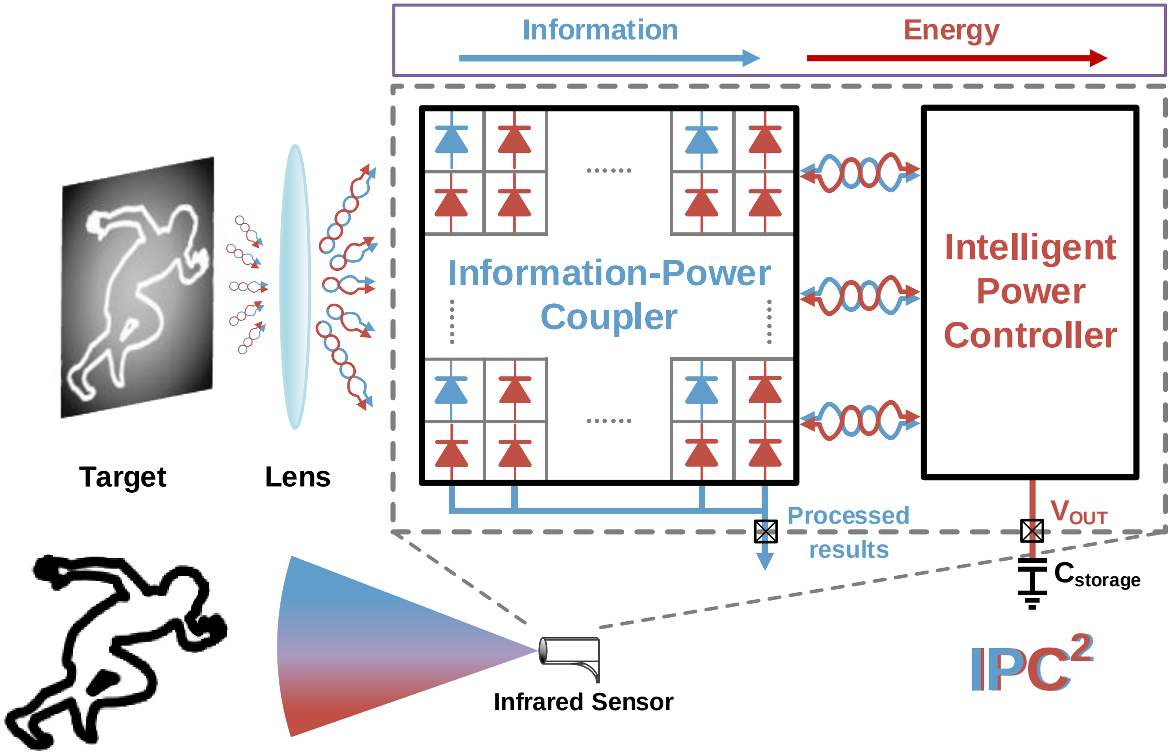
Background

- Energy and information are deeply entwined, mutually constraining and complementing each other.



- FEI: Fusion processing of sensing Energy and Information
  - Exploit the natural merit.
  - Energy-efficient and self-sustainable.
  - Enables energy harvesting and information processing on the same focal plane.

FEI: Fusion processing of sensing Energy and Information



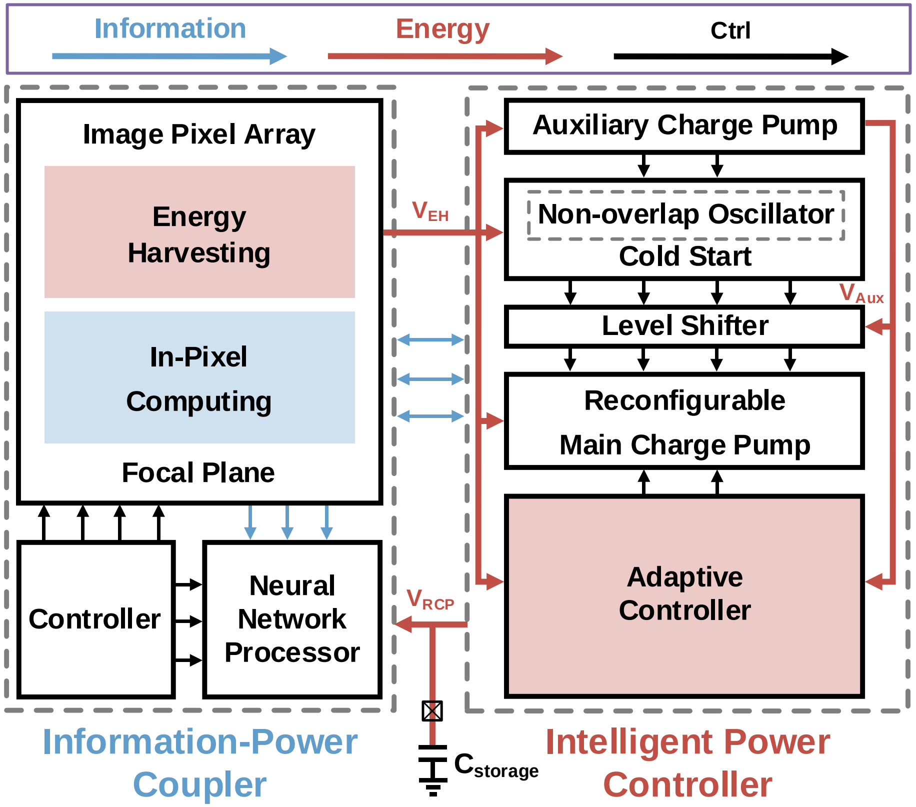
- Simultaneous energy harvesting and low power in-pixel-computing.
- Schedule the harvested energy to complete low power NN inference.
- Software-hardware co-design strategy to exploit the layer-wise characteristic of the computation process and circuit topology.

The IPC² System

- **IPC²** System
  - Fusion processing of sensing energy and information

- **IPC_p**
  - Information-Power-Coupler
  - Utilizes in-situ coupled energy to process the containing information on the same focal plane

- **IPC_{trl}**
  - Intelligent-Power-Controller
  - Scheduling the harvested energy self-adaptively



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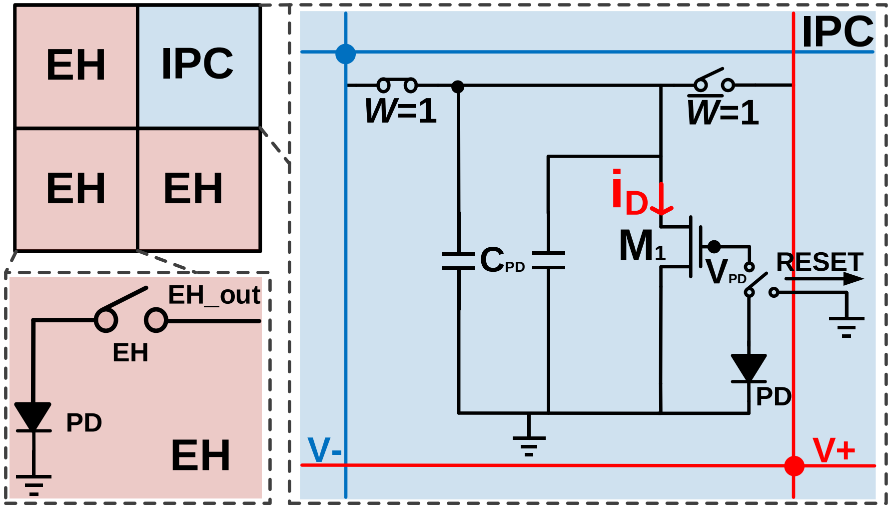
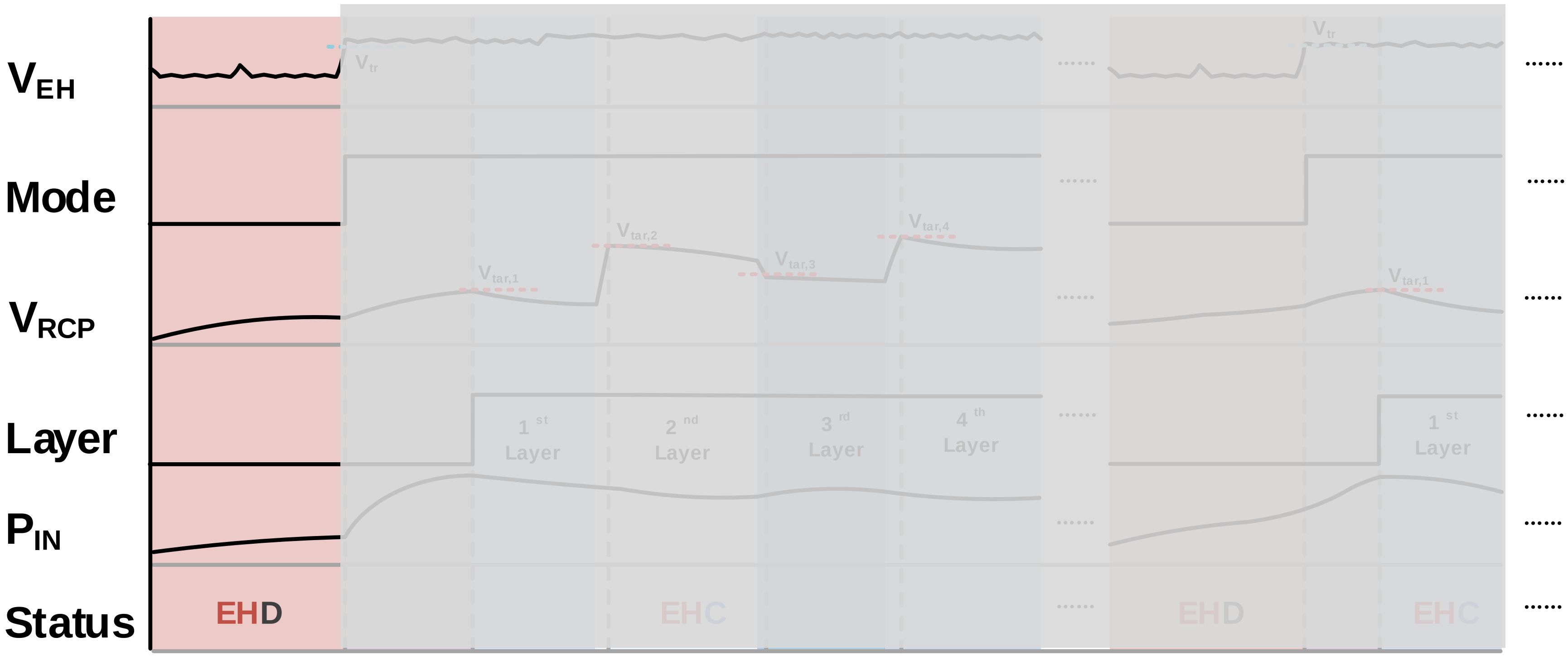
IPC_p: Information Power Coupler

- Zero-biased PD for energy harvesting and information processing in the analog domain.
- EH pixel: Sensing and energy harvesting.
- IPC pixel: In-pixel-computing circuit.
- 1st layer of NN inference on focal plane.



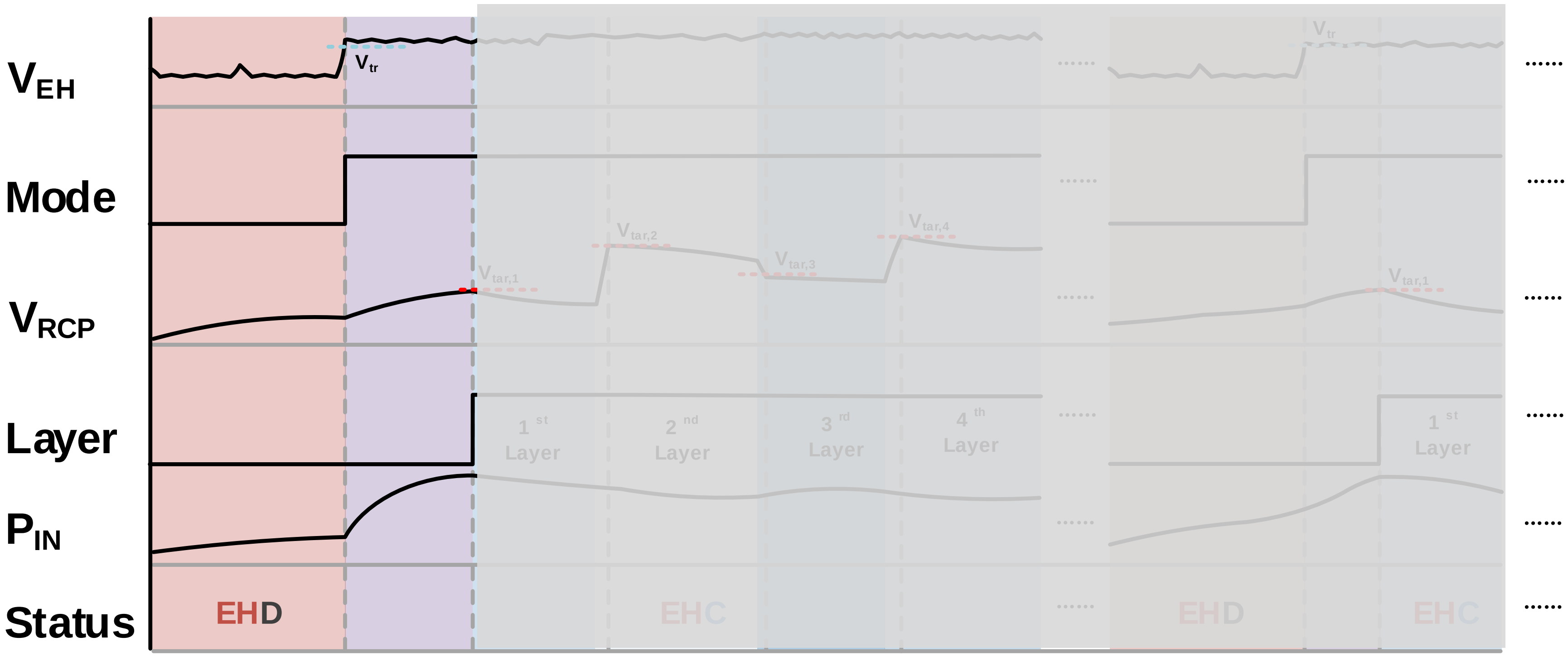
(a) (b)

IPC$_p$: Information Power Coupler



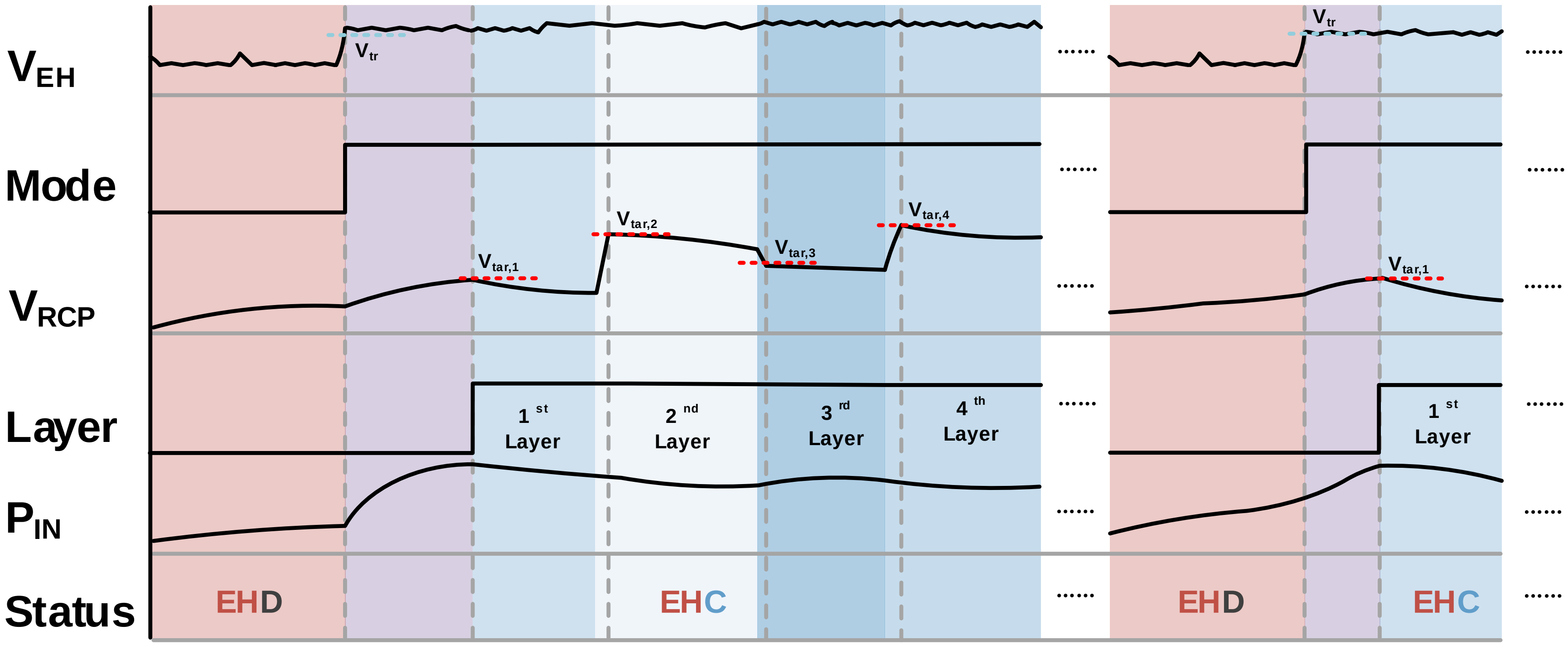
- Initial stage: No target is in sight.
- EHD mode: Energy Harvesting and Detection.
- EH pixels start working, IPC pixels are off.
- Energy is accumulated to the off-chip capacitor.
- IPC$_{trl}$: Cold start.

IPC$_p$: Information Power Coupler



- A target appears in the view.
- Stronger energy on the focal plane.
- Useful information has been detected.
- EHC mode is triggered: Energy Harvesting and Compute.
- EH pixels are working, IPC pixels are still off.

IPC$_p$: Information Power Coupler



- V_{RCP} reaches $V_{tar,1}$: Low power in-pixel compute begins.
- EH pixels are working, IPC pixels are working.
- Harvested energy as a complementary to the storage capacitor.
- The in-pixel compute is powered by harvested energy.
- **Fusion processing of sensing energy and information.**

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IPC_{trl}: Intelligent Power Controller

- The adaptive design flow:
  - Step1: Determine the neural network layer-wise target operation voltage. $\longrightarrow$ $V_{RCP_{tar,i}}$
  - Step2: Adjust the reconfigurable main charge pump's topology. $\longrightarrow$ $\boldsymbol{Stage\ number\ N}$
  - Step3: Improve the energy efficiency by matching impedance of interfaces. $\longrightarrow$ $\boldsymbol{Capacitance\ of\ each\ stage\ C_{stage}}$

IPC_{trl}: Intelligent Power Controller

- Step1: Determine the neural network layer-wise target operation voltage.
  - The inference energy consumption E_{Layer} for each NN layer

$$E_{Layer} = \frac{V_{Layer}^2}{R_{Load}} t_{op}$$

  - The required operation voltage $V_{RCP_{tar},i}$ for each neural network layer

$$V_{RCP_{tar},i} = V_{min} + \frac{OP_{max} - OP_{current}}{OP_{max} - OP_{min}} (V_{max} - V_{min})$$

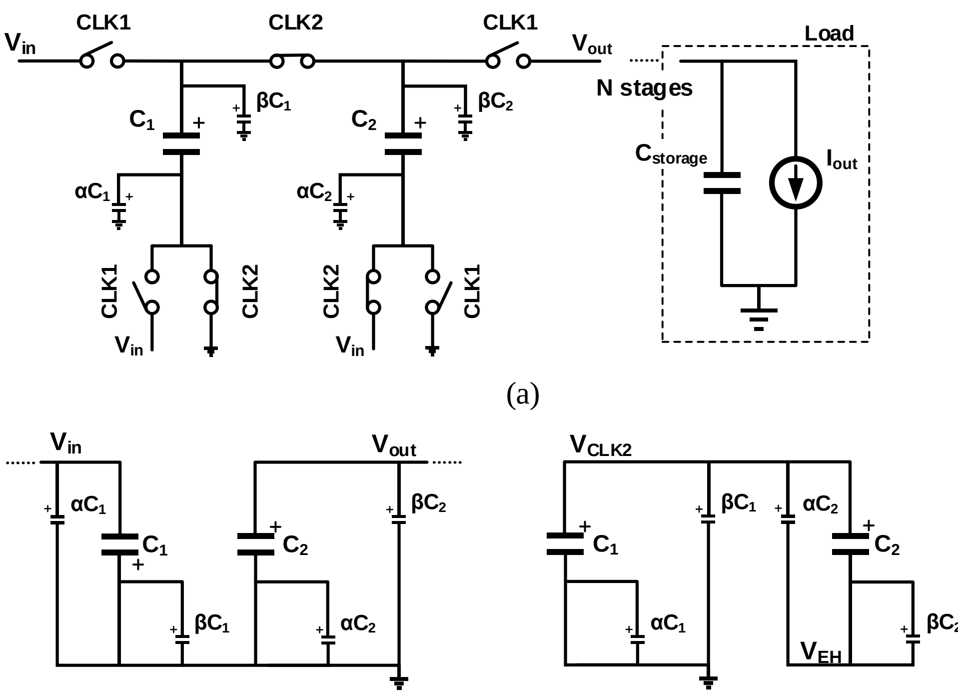
- Lower operation voltage for layers with more operation numbers
- More energy consumption reduction
- Executed self-powered NN inference with less delay

*For more detail : reference [6]

IPC_{trl}: Intelligent Power Controller

- Step2: Adjust the reconfigurable main charge pump's topology.
- The equivalent model of two stages capacitive charge pump.
  - Driven by non-overlap oscillator.
  - Parasitic capacitors and current load are considered.

Notations	Definition
V_{EH}	The converted voltage from harvested energy.
V_{in}	The input voltage for each stage.
T_{RCPtar}	The required output voltage for each layer.
$C_{storage}$	The capacitance for energy storage.
C_{stage}	The capacitance in each stage.
α	The parasitic parameter of the top plate of capacitor.
β	The parasitic parameter of the bottom plate of capacitor.
$t_{oscillator}$	The period of the oscillator.
N	The stage number of the charge pump.



(a) (b) (c)

IPC$_{trl}$: Intelligent Power Controller

- Algorithm for transient analysis.
- Initialize and definition
  - Initial stage number:
  - $N = 0$
  - Start with CLK1 phase:
  - $CLK = 0$
  - Begin charge transfer:
  - $Q_{CLK2} = 0$
  - $V_{in} = V_{CLK2} = V_{EH}$
  - $V_{out} = 0$
  - Charge consumption by the load:
  - $Q_{Load} = V_{out} C_{storage} - I_{out} t_{oscillator}$
  - Total capacitance at CLK1 phase:
  - $C_{CLK1} = (\alpha + 1) C_{stage}$
  - Total capacitance at CLK2 phase:
  - $C_{CLK2} = \left(\frac{\alpha}{\alpha+\beta} + \alpha + 1\right) C_{stage}$

IPC_{trl}: Intelligent Power Controller

- Transient analysis of charge pump to get N.
  - **while** $V_{RCP_{tar}} < V_{RCP_{act}}$ **do**

    if $CLK = 0$ **then**

    $$Q_{in} = Q_{CLK2}$$
    $$V_{in} = Q_{in} C_{CLK1}$$
    $$V_{out} = V_{out}$$
    $$Q_{out} = V_{out}\left(\frac{\alpha}{\alpha+1} + \beta\right) C_{stage}$$
    $$V_{RCP_{act}} = V_{out} - Q_{Load} C_{storage}$$
    $$N++$$
    $$CLK = 1$$

    else

    $$Q_{CLK2} = Q_{out} + V_{in}\left(\frac{\beta}{\beta+1} + \alpha\right) C_{stage}$$
    $$V_{CLK2} = Q_{CLK2} C_{CLK2}$$
    $$V_{out} = V_{CLK2}$$
    $$Q_{CLK2} = V_{CLK2}\left(\frac{\alpha}{\alpha+1} + \beta\right) C_{stage}$$
    $$N++$$
    $$CLK = 1$$

    end if
  - **end while**
  - **return** N

The topology at CLK1 / CLK2 phase.

IPC_{trl}: Intelligent Power Controller

- Step3: Improve the energy efficiency by matching impedance of interfaces.
  - The inversely proportional relationship:

$$R_{IPC_{trl},input} \propto \frac{t_{oscillator}}{NC_{stage}}$$

  - By adjusting $t_{oscillator}$ or C_{stage} , a proper $R_{IPC_{trl},input}$ can be achieved.

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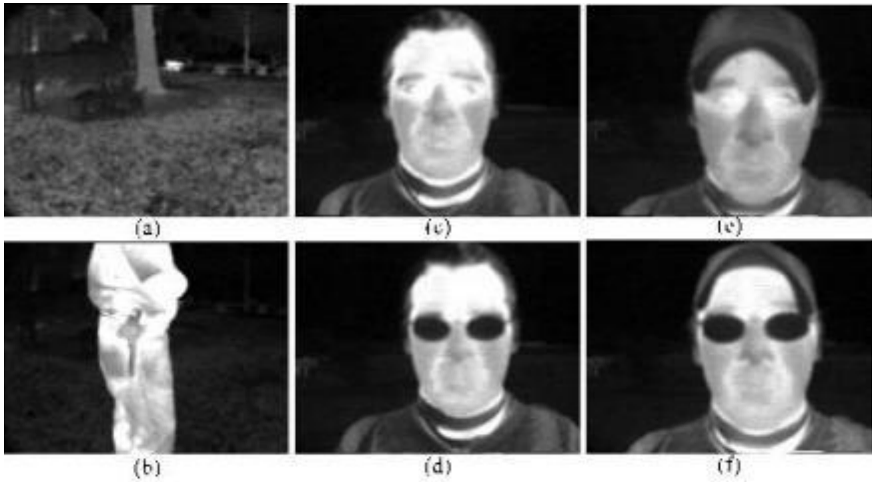
Simulation Results

- The proposed architecture and design strategy are simulated with TSMC 180nm technology.
- The entire pixel array
  - 128×128 PDs for sensing
  - 32×32 PDs for IPC -> 1st layer of BNN inference
  - 15,360 PDs for energy harvesting
- The Compute In Memory (CIM) structure[7]
  - Complete the computation of subsequent BNN layers
- Intelligent-power-controller (**IPC$_{\mathbf{trl}}$**)
  - Energy efficiency power management

Simulation Results

- **The implement of IPC_{trl}:**
  - Conv2 takes the highest power reduction ratio(**30.57%**).
  - Total energy consumption of conducting a BNN in IPC^2 system is **only 147.62nJ**.
  - Eliminate **25%** energy consumption.



Two datasets from the OTCBVS Benchmark Dataset Collection[8]

	Conv2	Conv2	FC1	FC2
Operation Number	**4,515,840**	**2,654,208**	**276,480**	**960**
Operation Voltage (V)	**1.000**	**1.082**	**1.188**	**1.200**
Energy / Option (fJ)	**17.24**	**20.18**	**24.33**	**24.83**
Energy @ IPC_{trl} (nJ)	**77.853**	**53.562**	**6.727**	**0.024**
Energy @ 1.2V (nJ)	**112.128**	**65.904**	**6.865**	**0.024**
Energy Reduction Ratio (%)	**30.57**	**18.73**	**2.01**	**/**

Simulation Results

	This Work	ISSCC 2023[9]	TCAS-I 2017[10]	JSSC 2020[11]
Process	180 nm	180 nm	130 nm	180 nm
Supply Voltage	1 – 1.2 V	0.9 – 1.2 V	1.2 V	1.2 V / 0.8 V
Power	350.07 nW [a]	3.6 μW @ 1 fps	13.9 μW @ 230 fps	2.36 μW
Energy Efficiency	9.23 pJ / pixel / frame	55 pJ / pixel / frame	1130 pJ / pixel / frame	11.4 pJ / pixel / frame
Self-powered Frame Rate	4 fps [b]	1 fps	230 fps	15 fps
Function	Target Detection & NN Inference	Image & ND + ED [c]	Moving Object Detection	Image & MS + OS [d]
Accuracy	Self-powered NN Inference: 99.4 %	Positive ND: 85.2 % Negative ND: 86.2 %	N/A	N/A
Energy Harvesting	YES	YES	YES	NO
Energy Conversion	93.38 %	N/A	Boost: 76 % Buck: 54 %	N/A
Intelligent Power Control	YES	NO	NO	NO

[a] Power consumption of IPC.

[b] Self-powered frame rate for the complete neural network.

[c] ND: Novelty Detection; ED: Edge Detection.

[d] MS: Motion Sensing; OS: Object Segmentation.

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Conclusion

- **A Fusion processing strategy (FEI) of sensing Energy and Information for infrared smart vision system is detailed.**
  - Simultaneous energy harvesting and low power in-pixel computing
  - Utilizing in-situ coupled energy to process the containing information on the same focal plane.
- **An IPC^2 system combines low power information-power-coupler (IPC_p) with intelligent-power-controller (IPC_{trl}) is presented.**
  - The architecture demonstrates a scheduling method for deeply fused energy and information circumstances.
- **A software-hardware co-design strategy is proposed.**
  - Considering power consumption characteristics of the computing process to determine the topology and parameters IPC_{trl}.

Thanks for listening!
Q&A

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