Biologically Inspired Vision Systems in Standard CMOS

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30 THIRTY YEARS OF SYSTEMS RESEARCH EXCELLENCE

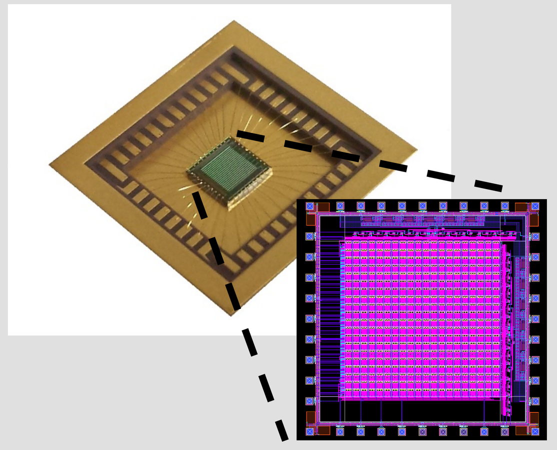
INSTITUTE FOR SYSTEMS RESEARCH
A. JAMES CLARK SCHOOL OF ENGINEERING

Current Research: CMOS Imagers

Our lab has developed specialized CMOS imagers with a focus on:

- biosystem applications such as lab-on-chip systems
- flight stabilization for unmanned aerial vehicles
- image plane processors
- medical diagnostics.

Commercial CMOS imagers are ubiquitous in our every day devices. They are cheap, achieve high sensor densities, and easily integrate with other electronics. This highly successful technology is based on the standard sensing system paradigm of front-end analog sensing, then conversion to digital, followed by digital processing. This approach does not fully utilize the capabilities that CMOS integrated circuits offer – namely, single chip integration of circuits and sensors.



In order to fully realize the potential of CMOS imagers, a systems-level design approach must be utilized with considerations of both the sensing measurement and the system-level functionality.

Future Research: Single Chip CMOS Image Processors

Future work will focus on the development of fully integrated, single chip solutions to vision problems that reduce size, weight, and power requirements to meet the needs of current and future microsystems. These vision systems will offer high performance, low-power consumption, and high functionality.

We are addressing these needs through innovative instrumentation techniques, adaptive circuits for high fidelity sensing and computation, and compact implementations of sophisticated image and video processing techniques.

Applications for such vision systems include:

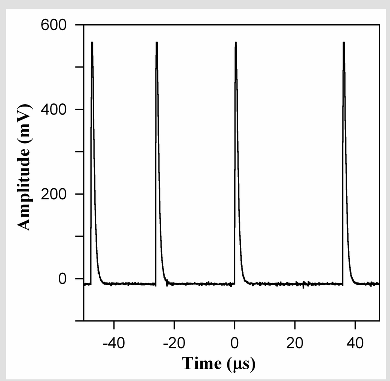
- Advanced imagers for lab-on-CMOS applications
- Vision-based navigation and stabilization for autonomous robotic platforms
- High dynamic range imagers for day/night operation
- Computational imagers for computer vision systems
- Time-resolved fluorescence spectroscopy

Picture of Crazyflie, Source: www.geek.com

Single Photon Avalanche Diodes

- Traditional CMOS imagers use long integration times to overcome weak optical signals and noise
- Time-correlated imaging requires single photon sensitivity with sub-nanosecond temporal resolution … traditional techniques can't do this!
- Strategy: high sensor gain improves temporal dynamics and sensitivity

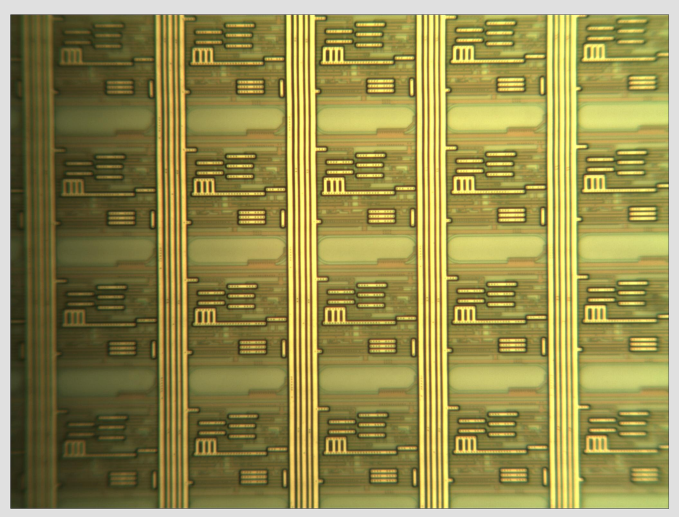
- Single photon avalanche diodes (SPADs) are PN junction diodes reverse biased above breakdown
- High gain (>10^6) through avalanche breakdown
- Fabricated in standard CMOS
- Single photon sensitivity
- Sub nanosecond timing resolution



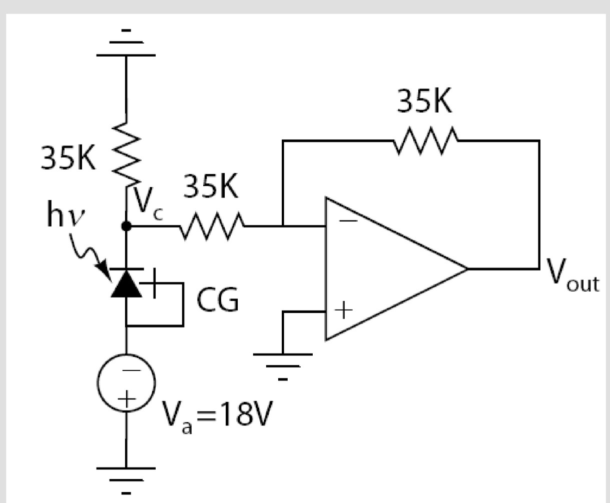
Detector voltage vs time

Like biological photoreceptors, SPADs do not follow the paradigm of traditional synchronous imaging. They are event-based and generate digital pulses in response to individual photons.

- Intrinsically digitize signal during detection
- High event rates (>10MHz)
- Wide dynamic range (>100dB)



Photomicrograph



Readout circuit w/ passive quenching

Adaptive Integrated Circuits

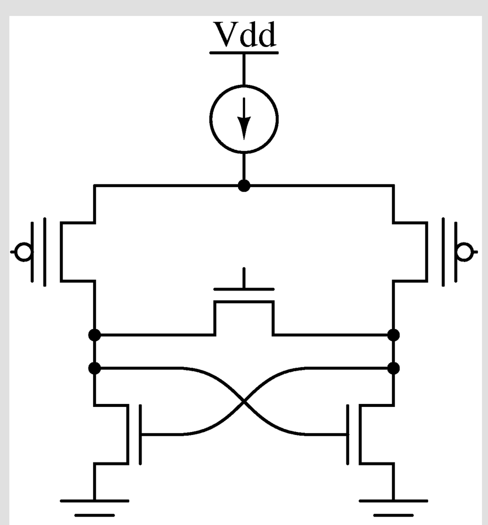
Analog circuits are often required to sense phenomena in the analog world. They offer a small footprint and low power consumption but are susceptible to interference & mismatch, motivating the need for trimming their parameters.

- Matched analog devices are large and expensive
- Currently, many sensors are calibrated post-fabrication and post-sensing by digital signal processing (DSP) techniques
- Alternative strategies for parameter matching include adaptive analog circuits

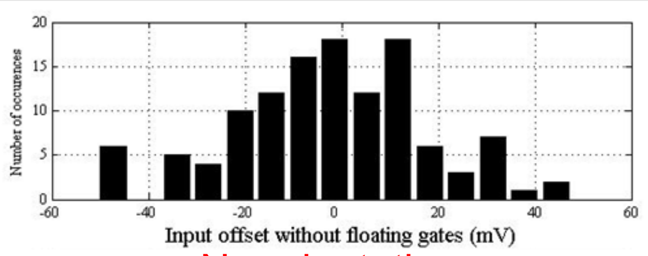
Biological systems employ highly effective adaptation techniques. They use multiple, hierarchical, nested stages of adaptation to boost dynamic range, reduce power consumption, and handle high levels of mismatch. They offer design inspiration for analog and mixed-signal circuit design

Simple 5-transistor comparator w/ floating gates

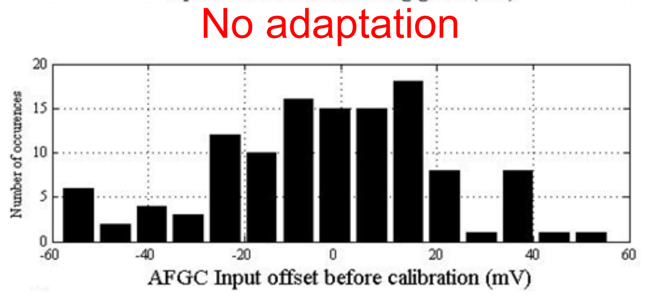
- Two phases of operation
  - Reset: outputs equilibrate
  - Evaluation: decision latched
- Programming
  - Encompasses entire system from input to output
  - Occurs when power supply is raised



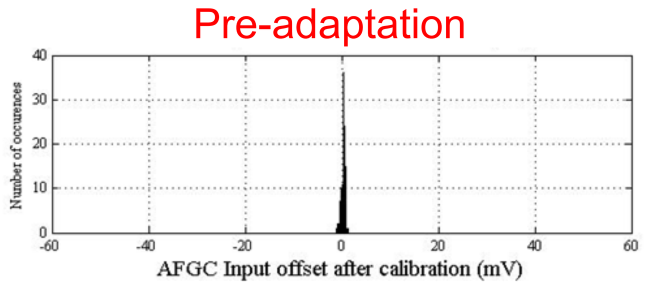
Simple 5T Comparator



No adaptation



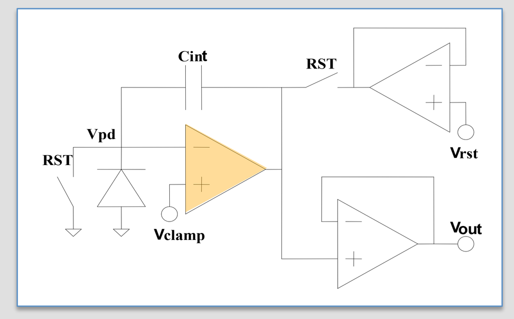
Pre-adaptation

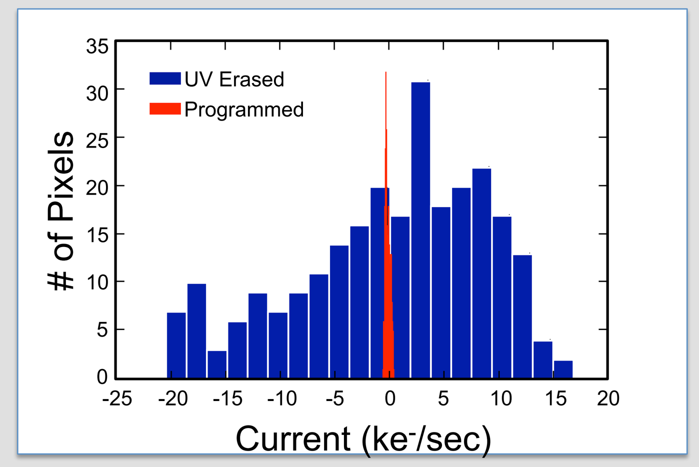


Post-adaptation

Capacitive Trans-Impedance Amplifier

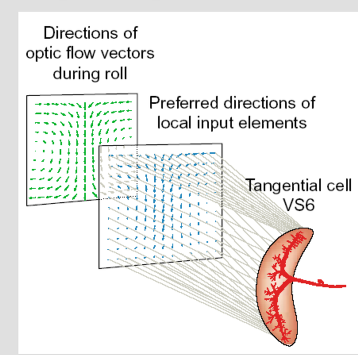
- Photomultiplier tubes (PMTs) are the gold standard for detecting really weak light, but …expensive, fragile, bulky
- CMOS detectors are cheap, robust, small but … high noise!
- Strategy: suppress photodiode dark current by collecting carriers at zero bias voltage
- BUT … input offset of integrating amplifier limits ability to reduce dark current (must be <1 mV accuracy)
- Solution: use adaptation
- Performance becomes comparable with commercial PMTs



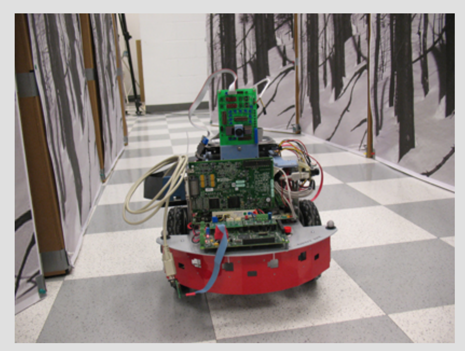


Single Chip Motion Estimation

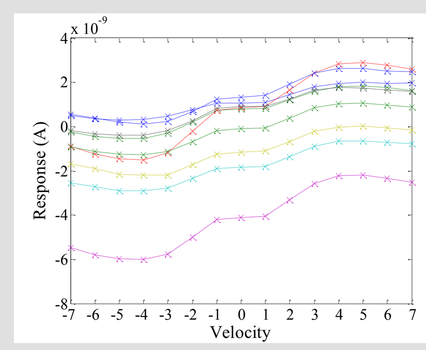
- On-chip optic flow computation and spatial filtering for autonomous navigation
- Spatial pattern of optical motion provides information about self motion and environmental cues
- Can be used for visual navigation and stability



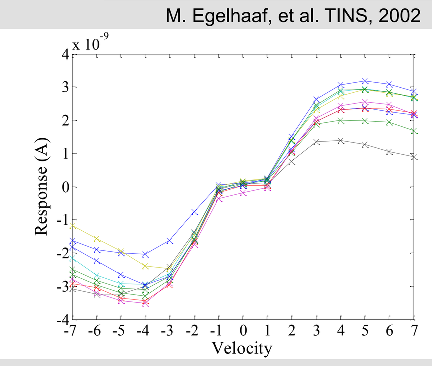
M. Egelhaaf, et al. TINS, 2002



Chip power: 42μW



Pre-adaptation



Post-adaptation

Awards CCF0238061 and IIS0515873

AFOSR
Centeye

Phase II STTR award #FA8651-14-C-0107

The MOSIS Service

Acknowledgements: Chip fabrication by MOSIS. Robotic experiments in collaboration with Sean Humbert, Aerospace Engineering, UMD.

Integrated Biomorphic Information Systems Lab