Towards “Eyes” for Sensor Network Systems

Andreas G. Andreou
Electrical and Computer Engineering and
Whitaker Biomedical Engineering Institute
Johns Hopkins University
http://www.ece.jhu.edu/faculty/andreou/AGA/index.htm
outline

• “Ears” for sensor network systems: a brief detour
• Introduction
  – Light, photons, noise, bandwidth
  – Current signal processing and translinear networks
• Systems
  – Polarization contrast chip
  – Spatial-temporal processing
  – Ego-motion compensation chip in a balloon observatory
  – Network architecture for distributed feature extraction.
• Conclusions
smart microphone project

4 chamber acoustic horn

Cross-Correlation ASIC

Gradient Flow ASIC

Auto-Correlation Wake-Up ASIC

Power Strobe Circuit

4 MEMs Microphones

http://www.signalsystemscorp.com/acoustic_surv.htm
and some related papers


what did we learn?

- COTS can take you up to a point.
- DSP and FPGA also take you up to a point, custom analog or digital design is necessary.
- Event based, one bit digital processing.
- Interfaces are critical! —necessity for system level design-
- Algorithm exploration is necessary with real data and the actual application environment.
- Wireless data communication is expensive; do the computation locally if you can!
- Analog subthreshold CMOS works well if designed properly!
the energy cost of bits – in wires and wireless –

![Graph showing bit energy vs distance with various data points for different technologies including UWB: 03267r6P802-15_TG3a and Chipcon Datasheets: www.chipcon.com]
the not-so-state-of-the-art not-eye

CrossBow MTS310CASensorBoard

Clairex CdSe photoconductor
~ 2 mW power (light ON)
~ 47 uW power (light OFF)
~ 10 kHz bandwidth
5 Volts power supply (signal)
10 bits ADC, 15 KS/s

13 nJ per bit of light data –NOT information-

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Material Type</th>
<th>( \lambda_\text{m} ) nm</th>
<th>( R_{\text{ON}}^{(1,2)} ) ( \Omega ) (typ)</th>
<th>( R_{\text{OFF}}^{(3)} ) ( \Omega ) (min.)</th>
<th>( V_{\text{meas}}^{(4)} ) Volts</th>
<th>( V_{\text{max}} ) Volts</th>
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<tr>
<td>CL9P4L</td>
<td>4, CdSe</td>
<td>690</td>
<td>2.0K</td>
<td>520K</td>
<td>8.0</td>
<td>170</td>
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http://www.clairex.com
“eyes” for sensor network systems

Eyes: sensory structures capable of spatial vision, i.e. imaging the environment, no matter how crude the image is

*Land and Nilsson, Animal Eyes*

- Is there something interesting in the environment?
  - in a specific class of objects
- Where is it?
- What is it?

often it is about a few bits in the right place at the right time
the way natural eyes see

- Continuous sensing
- Polarization sensitivity
- Contrast sensitivity
- Local gain control
- Spatial filtering
- Temporal filtering
- Sampling on demand
light, photons, photon shot-noise, bandwidth …
analog, digital and all that …

<table>
<thead>
<tr>
<th>CVDT</th>
<th>Continuous-Value</th>
<th>Discrete-Time</th>
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<tbody>
<tr>
<td>CCD</td>
<td>Continuous-Value-Discrete-Time</td>
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<td>Switched Capacitor</td>
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<thead>
<tr>
<th>CVCT</th>
<th>Continuous-Value</th>
<th>Continuous-Time</th>
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<tr>
<td>Linear and non-linear analog</td>
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<tr>
<th>DVDT</th>
<th>Discrete-Value</th>
<th>Discrete-Time</th>
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<td>Multivalue digital</td>
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<th>DVCT</th>
<th>Discrete-Value</th>
<th>Continuous-Time</th>
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<tbody>
<tr>
<td>Asynchronous digital</td>
<td></td>
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<tr>
<td>Neuron spikes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anisochronous Pulse Time Modulation</td>
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</table>
subthreshold CMOS

- Current is exponential function of the terminal voltages $V_s$, $V_b$, $V_g$, $V_d$
- Large dynamic range
- High gain (transconductance)
- Low saturation voltage $V_{dsat} \sim 100\text{mV}$
- Lossless channel and source/drain symmetry (diffusive networks)
- Zero conductance control node (gate); possibility of floating gate for long term charge storage
- Mobility considerations
- Frequency limitations

\[ f_{T,\text{max}} = \frac{g_m}{2\pi C} \frac{\mu V_t}{\pi L^2} \]

$1\mu m \rightarrow 100\text{MHz}$  
$0.25\mu m \rightarrow 1.6\text{GHz}$
subthreshold MOS and bipolar characteristics

\[ I_D = I_{DS} = S I_{n0} \exp \left( \frac{\kappa n V_{GB}}{V_t} \right) \left[ \exp \left( \frac{V_{SB}}{V_t} \right) - \exp \left( \frac{-V_{DB}}{V_t} \right) \right] \]

\[ I_D = I_{SD} = S I_{p0} \exp \left( \frac{-\kappa p V_{GB}}{V_t} \right) \left[ \exp \left( \frac{V_{SB}}{V_t} \right) - \exp \left( \frac{V_{DB}}{V_t} \right) \right] \]

\[ IC = I_S \exp \left( \frac{V_{BE}}{V_t} \right) = I_S \exp \left( \frac{V_B - V_E}{V_t} \right) \]
symmetric MOS model

\[ I \equiv I_{Q_s} - I_{Q_d} = \mu \frac{W}{L} \left[ \frac{1}{2} \frac{Q_s^2}{C_{ox} + C_{dep}} + \frac{kT}{q} Q_s \right] - \left( \frac{1}{2} \frac{Q_D^2}{C_{ox} + C_{dep}} + \frac{kT}{q} Q_D \right) \]

\[ I_{SD} \propto F(V_{GB}, V_{SB}) - F(V_{GB}, V_{DB}) \]

\[ I_{SD} \propto G(V_{GB}) \left[ H(V_{SB}) - H(V_{DB}) \right] \]
non-linear CMOS resistors and translinear grids

Linear conductances

\[
\begin{align*}
V_r - V_P &= G_1 I_P \\
V_r - V_Q &= G_1 I_Q \\
V_P - V_Q &= G_2 I_{PQ}
\end{align*}
\]

\[
I_{PQ} = \left( \frac{G_1}{G_2} \right) (I_Q - I_P)
\]

NMOS only “diffusor/conveyor”

\[
I_{PQ} = \left( \frac{S_h}{S_v} \right) \exp \left[ \frac{\kappa_n V_C - \kappa_n V_r}{V_T} \right] (I_Q - I_P)
\]

1D spatial averaging network

\[ I^*_j = I_j + \left( \frac{S_h}{S_v} \right) \exp \left( \kappa_n v_C - \kappa_n v_r \right) \left( 2I_j - I_i - I_k \right) \]

Normalizing inter-node distances to unity we write the above on the continuum

\[ I^*(x) = I(x) + \lambda \frac{d^2I}{dx^2} \]

where \( \frac{d^2I}{dx^2} \approx 2I_j - I_i - I_k \)

Find the smooth function \( I(x) \) that best fits the data \( I(x) \) with the minimum energy in its first derivative.

\( \lambda \) The regularization parameter cost associated with energy in the derivative relative to the squared error of the fit to the data

Inputs:
\[ I_i^*, I_j^*, I_k^*, I^*(x) \]

Outputs:
\[ I_i, I_j, I_k, I(x) \]

At node \( V_j \):
\[ I_j^* = I_{ij} - I_{jk} + I_j \]
sensor level processing: what and where

Pixel:
- transduction
- amplification
- gain control
- quantization
- non-uniformity correction
- spatial filtering
- temporal filtering

Periphery:
- ego-motion
- moments
- global contrast
- data-communication
seeing in ways that we can’t!

doing things in front of the pixel: micropolarizers


current-mode translinear processing
sensor level processing: what and where

Pixel:
- transduction
- amplification
- gain control
- quantization
- non-uniformity correction
- spatial filtering
- temporal filtering

Periphery:
- ego-motion
- moments
- global contrast
- data-communication

The diagram shows a pixel and its computational circuits, along with the select rows and columns. The pixel includes functions for transduction, amplification, gain control, quantization, non-uniformity correction, and spatial and temporal filtering. The periphery includes functions such as ego-motion, moments, global contrast, and data-communication.
spatial/temporal filter

33 x 30 pixels 0.5 micron linear capacitor triple metal CMOS
50 micron cell pitch (2 x 2 mm die)
sensor level processing: what and where

Pixel:
- transduction
- amplification
- gain control
- quantization
- non-uniformity correction
- spatial filtering
- temporal filtering

Periphery:
- ego-motion
- moments
- global contrast
- data-communication
doing things in the sides

Flare Genesis Observatory

http://sd-www.jhuapl.edu/FlareGenesis/flare.html

- Balloon based observatory
- Truly autonomous – low bit rate link -
  - A three stage hierarchical system of sun orientation and tracking
  - Two “Eyes” for finding the sun and motion stabilization + Kodak Megaplus CCD camera
- Solar power; command and control power budget ~1W
networks of nodes ....constraints ....

Image sensor constraints (1280x1024 pixels, 24 bit/pixel, 10000 frames/s)

<table>
<thead>
<tr>
<th>Rates</th>
<th>Scanned</th>
<th>Anisochronous event based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate (Mbits/s)</td>
<td>24,000</td>
<td>variable</td>
</tr>
<tr>
<td>Distance (m)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Energy per bit (pJ)</td>
<td>20 x (bits/frame)</td>
<td>20</td>
</tr>
<tr>
<td>Latency (ms)</td>
<td>0.1 (frame rate)</td>
<td>0.00001 (pixel)</td>
</tr>
</tbody>
</table>

RF link constraints

<table>
<thead>
<tr>
<th>Rates</th>
<th>UWB (Multiband OFDM)</th>
<th>COTS (Chipcon 24xx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate (Mbits/s)</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>Distance (m)</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Energy per bit (nJ)</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Latency (ms)</td>
<td>0.01</td>
<td>100s</td>
</tr>
</tbody>
</table>
analog, digital and all that …

| CVDT            | Continuous-Value Discrete-Time | CCD  
|                |  
| DVDT            | Discrete-Value Discrete-Time | Switched Capacitor  
|                |  
| CVCT            | Continuous-Value Continuous-Time |  
|                |  
| discontinous    | Continuous-Time Continuous-Time | Linear and non-linear analog  
|                |  
| DVCT            | Discrete-Value Continuous-Time | Asynchronous digital 
|                |  
|                | Neuron spikes  
|                | Anisochronous Pulse Time Modulation |
event based systems

Pixel:
- transduction
- amplification
- gain control
- quantization
- non-uniformity correction
- spatial filtering
- temporal filtering

Periphery:
- ego-motion
- moments
- global contrast
- data-communication

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digital event based imager

high slew rate gain at low energy costs
the network is the architecture

ALL COMPUTATION DONE ON THE ADDRESSES OF THE EVENTS
distributed network processing

- Information is encoded in a stream of events, the address of each pixel node
  - Address Event Representation
  - Asynchronous on demand
- Programmable communication processors transform and route the events
- Local Processors perform spatial/temporal integration and normalization
- Point-to-point and broadcast links provide high speed interconnects
simulation …

(a) Input
(b) Output of stage 1
(c) Output of 60° stream
(d) Output of 0° stream
(e) Output of 120° stream
(f) Output of stage 2
feature extraction through projective fields

Think of computation as part of the MAC layer

results

Input

Rectified Laplacian (Matlab)

PrAER chip

PrAER (Matlab)
and something about biology: blow-fly photoreceptor

some final thoughts

- One size perhaps does not fit all!
- With multiple interacting points of view, is worth revisiting “polarization vision”.
- Asynchronous on demand systems may be preferable to random access or scanned for giving information to the question: “is there anything of interest out there?”
- CMOS imagers can be cheap and can be designed to specific applications; 0.5 micron CMOS may be a sweet spot for garden variety “eyes”.
- Increased physical complexity; more than just visible; large area sensor devices conformal to non planar surfaces.
- What good are “eyes” without optics or when they can’t move?….. Good questions! “eye” designers have plenty things to do.
acknowledgments:

- DARPA N0014-00-C-0315 Acoustic Microsensors
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- NVSED Smart focal planes

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Pedro Julian
Pablo Mandolesi
Eugenio Culurciello
subthreshold CMOS challenges: noise

\[ S(f)_{total} = \frac{K g_m^2}{f_A f} + 2qI_d. \]
energy costs per pixel

\[ P : \text{power} \quad (\text{Watts}) \]
\[ \xi : \text{pixel activity factor} \]
\[ N : \text{number of pixels} \]
\[ N_{\text{kernel}} : \text{number of pixels in the computational kernel} \]
\[ I_{bg} : \text{mean photocurrent (A)} \]
\[ I_{\text{comp}} : \text{computational branch current (typically 10–100nA)} \]
\[ V_{pd} = V_{\text{scale}} : \text{phototransduction branch voltage (typically (0.3) = 0.3 Volts)} \]
\[ V_{\text{comp}} = V_{\text{scale}} + V_{\text{sat}} : \text{computational branch voltage (typically (0.3 + 0.2) = 0.5 Volts)} \]

- Bandwidth scales linearly with computational branch current
- Power will scale linearly with computational branch voltage
Transduction and Dynamic Range Compression (I): Temporal

1. Average signal in time and store the state-range- on a quasi floating gate (Vfb)
2. Employ negative feedback to position the DC operating point.
3. Amplifier-computational branch-: single stage biased in subthreshold (100nA)

\[
P = (\xi I_{bg} V_{pd} + I_{comp} V_{comp})N
\]

\[
(0.1 \times 10^{-8} \times 0.3 + 10^{-7} \times 1) = 10^{-7} \text{W per pixel}
\]
Non-Uniformity Correction Using FGMOS

- An MOS mirror with FGMOS transistor (M2) injected using impact ionization (tunneling will work as well).
- NO power cost during operation.
- Technique can be applied to both current mode and voltage mode pixels.
- Energy cost only with initial calibration.
- Calibration takes ~2000 iterations for all pixels on the chip and each pixel takes about 1 sec.

\[
E_{\text{adapt}} = P \times T = N \times (I_{\text{in}}V_{pd} + I_{\text{out}}V_{\text{comp}}) \times T \\
= (10^{-8} \times 0.3 + 10^{-8} \times 10) \times 1 \\
= 10^{-7} \text{ Joules per pixel}
\]
Transduction and Dynamic Range Compression (I): Spatial -network based-

1. Average using a shunting network
2. Employ negative feedback and log-antilog amplifier to do the ratio computation
3. Note! kernel size does not matter as we normalize everything to the computational current and this gets steered from one pixel to the other.
4. Compression function not tanh but something that can be synthesized in CM circuits!

Boahen and Andreou 92

\[ I_{\text{out}} \rightarrow I_{\text{comp}} \quad I_{\text{in}} \rightarrow I_{\text{bg}} \]

\[ P = (\xi I_{bg} V_{pd} + I_{\text{comp}} V_{\text{comp}})N \]

\[ \frac{V}{V_s} = \frac{I^n}{I^n + I_s^n} \]
Center-ON-OFF surround with local competition and rectification

1. An alternative to resistive grids we can explicitly compute the Laplacian using simple scaled mirrors and summing the currents.

2. Added local wiring complexity

\[
C_0^0 = \begin{vmatrix}
I_0^{+60} - I_0^{-60} \\
+I_0^{+120} - I_0^{-120}
\end{vmatrix} - \alpha \left( C_0^{60} + C_0^{120} \right) - \beta \left( C_0^{+60} + C_0^{+120} + C_0^{-60} + C_0^{-120} \right)
\]

\[
P = (\xi \times 4 \times I_{comp} V_{comp}) N
\]

\[
(4 \times 10^{-8} \times 1) = 10^{-7} \text{W per pixel}
\]

Cauwenberghs and Waskiewicz 1999