BIO-INSPIRED ANALOG VLSI CIRCUITS
AND THEIR INDUSTRIAL APPLICATION

Eric Vittoz
CSEM Centre Suisse d'Electronique et de Microtechnique SA
CH-2007 NEUCHATEL, Switzerland

- Biology-inspiration
- Examples of industrial application
- Ongoing research
- Conclusion.
BIOLOGY AS A SOURCE OF INSPIRATION

In the continuous fight for survival all along evolution:
- life has invented increasingly complex solutions

Biology inspired systems:
- borrow some of them
- adapt to constraints of available technologies

Inspiration for VLSI processing circuits: from the brain
Different levels:
- Representation of signals and information
- Strategies
- Architectures
- Methodology
Opportunism:

Along evolution, life has made, step after step:
- best possible use of existing structures as...
- bootstrap for the next level of complexity.

Bottom-up approach, can be applied to VLSI:
- identify all properties of technologies, devices, circuits
- exploit them opportunistically to build more complex systems.

Also:
- explore potential of a solution in a broader range
- search for hidden advantages of apparent drawbacks.
OPPORTUNISM:

POSSIBLE FUNCTIONS OF MOS TRANSISTORS

- Switch (only function used in digital).
- Voltage-controlled conductance.
- Voltage-controlled current source.
- Multiplier \( (I_D \sim V_D \times V_G + \text{terms}) \).
- Functions \( x^2, \sqrt{x} \) (strong inversion: \( I_{D_{\text{sat}}} \sim V_G^2 + \text{terms} \)).
- Functions \( e^x, \ln(x) \) (weak inversion: \( I_{D_{\text{sat}}} \sim e^{V_G/nU_T} \)).
- Current memory (open or floating gate).
- Bipolar operation: precise \( e^x, \ln(x) \)
  - voltage and temperature references.
- Light sensor: any junction.

Can only be exploited in analog circuits.
PROSPECTS FOR ANALOG IN SIGNAL PROCESSING

- Point of view of power consumption:

(also, qualitatively: chip area)

Digital:
- Digital is more efficient for “traditional” processing
  - (also, qualitatively: precision, linearity)

Analog:
- Analog interfaces
- Collective processing in massively parallel systems.
- Goal:
  - make a decision
  - control an action

(also, qualitatively: precision, linearity)
With bipolar transistors:

\[ \sum_{cw} V_{BEi} = \sum_{ccw} V_{BEi} \quad \text{with:} \quad I_i = I_{Si} e^{V_{BEi}/U_T} \]

\[ \text{cw} = \text{clockwise} \]
\[ \text{ccw} = \text{counter-clockwise} \]

thus: \[ V_{BEi} = U_T \ln \frac{I_i}{I_{Si}} \]

which yields:

\[ \prod_{cw} I_i = \prod_{ccw} I_{Si} = \lambda \]

With MOS transistors in weak inversion:

poor precision acceptable for perceptive processing.
EXAMPLE OF TRANSLINEAR CIRCUITS

VECTOR-LENGTH CALCULATION

[Gilbert, 1975]

Current mode, provide: \( I_{\text{out}} = \sqrt{\sum I_i^2} \)

npn bipolar

p-MOS in weak inversion

\[ I_1 \quad I_{\text{out}} \quad I_2 \]

\[ + \quad + \quad + \]

\[ I_1 \quad I_2 \quad I_3 \quad I_{\text{out}} \]
Linear behaviour of transistors with respect to currents [Bult, 1992]

General case (any current level): same gate voltage

Special case of weak inversion ("diffusor" [Boahen, 1992]): different values of gate voltages possible, thus...
control of $G_i^*$ by gate voltage, or by...
control current $I_C$:

Thus: any network of linear controlled resistors can be implemented by transistors only.
Massive parallelism \((10^{11} \text{ neurons in brain})\)

VLSI technologies: towards billion-transistor chips

- large arrays \((10^2 - 10^6)\) of...
- simple cells \((10 - 10^3 \text{ tr.})\)
- low local speed \(<10\text{kHz}\)
- limited local precision thanks to...

Collective computation

- consensus of all cells on the best solution
- dense interconnections \((10^2 \text{ to } 10^5 \text{ synapses/neuron})\)
EXAMPLES OF COLLECTIVE OPERATORS

n Normalization [Gilbert, 1984]

\[ \sum_{i} I_{\text{outi}} = I_{\text{tot}} \]

Current gain same for all cells adjusts for: \( \sum I_{\text{outi}} = I_{\text{tot}} \)

n Winner-take-all [Lazzaro et al., 1988]

\[ I_{\text{outi}} = \begin{cases} I_{0} & \text{for largest } I_{\text{ini}} \\ 0 & \text{for others} \end{cases} \]

Points on largest current:

Value of largest current

n Consensus achieved by communication through single wire.
High connectivity is needed for collective computation but is a major obstacle for implementations in 2-dimensional VLSI. Possible (complementary) solutions:

- collective computation via single or few wire(s)
- communication with nearest neighbours only
- hierarchical interconnections (smaller density for larger distance)
- analog multiplexing:
  - standard row/column scanning
  - asynchronous and event driven
  - pulse communication.
COMMUNICATION BY ADDRESS-CODING EVENTS

- Common m-wire bus.
- Activity of each cell transmitted as...
- Frequency of address-coding events:

  ![Diagram](https://via.placeholder.com/150)

  code of address
  event (set of very short pulses)

- Features: - priority of access based on activity
  - no clock: phase of events is kept.

- Parallel access of all cells to the bus
  - with arbitration or...
  - without arbitration (random collisions)[Mortara, 1992]
**STRATEGIES**

- Learning from examples (instead of programming)
  - on-chip learning not very useful in practice but...
  - learning on computer during design phase
    resulting synaptic weights dumped on the chip.

- Adaptation
  - in time ("high-pass") , to eliminate constant information:
    novelty detector
    elimination of constant spatial noise of sensors.
  - to signal level, to cover wide dynamic range
    140 dB of external excitation
    40 dB of nerve activation
    very useful for analog VLSI processing
**RETINA FOR LOCAL ADAPTATION**

[Schematic for 1-D array]

- Real implementation:
  - 2-D array
  - Pseudo-conductances $R^*, G^*$

- $G(k)$ proportional to $I_{ph}(k)$ (local photocurrent)
  - $1/R(k)$ proportional to $F \cdot I_{ph}(k)$

- If $R(k) = 0$ then $\sum I_{out(k)} = \sum I_0$ : global normalisation

- If $R(k) > 0$, each $I_0$ distributed across area $A \sim L^2 = 1/(RG) \sim F$
  - Thus: local normalisation in adjustable area $A$. 

[Venier, 1997]
MEASUREMENTS ON LOCALLY ADAPTIVE RETINA

- Experimental 35x35 hexagonal array of pixels.
- Output communication by address-coding events.
- Checker-board illuminated by light gradient:
  - Dynamic range reduced to that of the object contrast.
Pulse representation *(in biology: spikes of action potential)*
- for communication
- for processing *(audition...ubiquitous?)*
  - time-domain processing
  - degree of coincidence of events
  - synchronization of processes

"Place coding" *(patterns of activity in 2D maps)*
Representation of a variable $x$:
set of nodes with preferred values $x_i$

$\mu_i$ (activation grade of node $i$)

particular value $x = \frac{\sum \mu_i x_i}{\sum \mu_i}$

Computation of $z = f(x, y)$ by network of links:
each link is a fuzzy AND gate

Advantages:
- continuous amplitudes
- high tolerance to perturbations
- low power in current mode
- systematic implementation of any function.
Biology-Inspired Analog VLSI:

EXAMPLES OF INDUSTRIAL APPLICATIONS
DETECTION OF MAXIMUM SPOT INTENSITY

[Chevroulet et al., 1995]

- Control of LCD protection screen
- Array of 26x26 pixels
  - light sensor
  - element of max.-current copier
- 18V generator, control and test
- 4x4.5 mm² in 2µm process
- Reacts in 50µs with 1mW.
CALCULATION OF 1-DIMENSIONAL MOMENTS

If: \( R_j = j^{n-1} R_1 \)

Then, the \( n \)th order moment of current distribution:

\[ M_{xn} = I_b \]

Center of gravity \( x_0 \):

1. \( n = 1 \) (\( R_j \) constant)
   \[ x_0 = \frac{M_x}{M_0} = \frac{I_b}{|I_a + I_b|} \]
MONITORING OF SOLAR ILLUMINATION

[Venier et al., 1996]

- Ambiance-control in vehicles
  - presence of sun
  - sun intensity
  - sun azimuth and elevation

- Array of 1365 pixels
  - organized in polar coordinates
  - light sensor
  - weighted copies of photocurrents

- Two linear pseudo-resistive networks
  - radial
  - angular

- Reacts in 1ms for 100µA
- Precision better than 15°.
MOTION DETECTOR FOR TRACKBALL

- Inspired from rabbit’s eye
- Ball with random pattern of dots
- Illuminated by periodic flashes
MOTION DETECTOR FOR POINTING DEVICE

[Arreguit et al., 1996]

- Calculation of the 2 comp. of translation of a random pattern of dots.
- Detection of horizontal (and vertical) edges E:
  \[ \Delta x (\text{or } \Delta y) = p \times \frac{\text{number of moving edges } E}{\text{total number of edges}} \]
- Identification of edges moving during \( \Delta t \) (between 2 snapshots)
- Motion during \( \Delta t \):
- Current mode analog processing
- Array of 75 cells, pitch \( p = 300 \mu m \)
- Resolution above 800 dpi
- Graceful degradation for defective cells.
Convolutive neural network.
- Abstraction level increases at each step.

All cells in same sub-layer have
- Same set of weights with shifted receptive field
  - Thus: shift invariant.

All cells in same column have same
- Receptive field.

Weights learned during design
- Implemented as capacitance ratios
THREE-LAYER CONVOLUTIONAL NEURAL NETWORK

[Masa et al., 1999]

- 100K capacitors (50K weights)
- 6x7mm² in 0.5 µm process
- Power consumption: <4mW
- Speed: 1000 images/s.
- Equiv. 10⁸ multiply and add/sec.
- Wide range of
  - fonts
  - quality of printing
- Graceful degradation with defects.
Biology-Inspired Analog VLSI:

ONGOING RESEARCH
FEATURE ENHANCEMENT

[Venier et al., 1997]

- Edge enhancement by diffusion in linear network (in retinal layer).
- Address-coding event communication to...
- Orientation enhancement by nonlinear unisotropic diffusion:

In one cell:

- Preferred orientation electrically adjustable.

Photo-receptors

Vertical

Orientation enhanced

Edge enhanced

Venier et al., 1997
n Retina 1 with narrow-field lens delivers high-resolution visual info.
  i moving optical front end (rotating prisms) to change gaze angle.

n Retina 2 with wide-angle watches the whole visual field.
  i saliency map (degree of interest of various parts in scene).

n Chip A controls saccadic exploration of interesting parts (targets).

n Chip B centers and tracks selected target in closed loop.
CHIP FOR SACCADES CONTROL

[Landolt, 1997]

Computes $\phi_1, \phi_2 = f(R)$ to center visual field of retina 1 on target.

Exploration time of targets function of their degree of interest.

Place-coding + communication by address-coding events.

160’000 transistors, 15’000 capacitors on 45mm $^2$ (0.5µm process).

Total power consumption at 5V: 5mW.
CHIP FOR VISUAL TO MOTOR MAPPING

Area: 2mm²

Incremental control: computes $\Delta \phi_1, \Delta \phi_2 = f(\phi_1, \phi_2, r)$ needed for $\Delta r$

Place coding; activation grade represented by:
- current (internal): 0...100nA
- pulse frequency (external): 0...1KHz

Total power consumption at 5V: 30µW
Analog Fuzzy Controller

\[ \text{Current splitters} \]

\[ \text{4-bit weighting of activities} \]

\[ \text{Bump circuit (input membership function)} \]

\[ \text{1 output} \]

\[ \text{(activity of rule n)} \]
FUZZY CONTROLLER CHIP

[Landolt, 1996]

- Rule array: 8 by 10
- Supply voltage: 1.8 V
- Power cons.: 850nW
- Input full scale: 1V
- Settling time: 0.5ms
- Accuracy: 2.6% RMS
- CMOS process: 2µm
- Chip core area: 1.2x1.1mm²
FUTURE DEVELOPMENTS

- Further exploration of existing techniques
  - Identification of new applications

- Exploration of new aspects:
  - Pulse processing (events in time)
  - Stochastic processing
  - Oscillatory behaviour of arrays of nonlinear cells
  - ......
EXAMPLE OF PULSE (SPIKE) PROCESSING

Extraction of voice pitch (frequency of amplitude modulation)

Behaviour of “chopper cell”:

$1/f_0$

$pulse$

$1/f$

effect of input

refractory $T_R$

integration

System architecture [van Schaik, 1998]:

silicon cochlea

Experimental results:

$1/f_M$

free-running ($f_0$)

synchronization $f = f_M$

output of coincidence array ($f_M = 130Hz$)

Application to voice separation?
CONCLUSION

Biology-inspired systems based on analog VLSI:
- still in infancy
- slowly growing

Potential already demonstrated by working chips:
- most of them still exploratory
- some have already resulted in innovative products.

Very attractive for low-power smart microsystems
- in particular for low-level vision.

May later compete with digital computation
- even when power is not limited
- for complex perception tasks.