Learning From Nature to Make Machines See and Robots Walk

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Nature’s Inspiration ....

Antoni Gaudi, *Casa Mila*, 1906 - 1910


After wikipedia.com
Nature’s Inspiration ....

Carver Mead, Neuromorphic Circuits, 1986 - 1990

After wikipedia.com
The Big Picture: Motivation

Developing Biomorphic Robotics

Restoring function after limb amputation

Adaptive Biomorphic Circuits & Systems

Restoring function after severe spinal cord injury
Presentation Outline

**Making Machines See**
- The biological visual system
- Silicon eyes and brains

**Making Robots Walk**
- The biological locomotion system
- Silicon spine and Walking robots

**Restoring Function to the Impaired**
- Spinal cord injury and locomotion prosthesis
- Gait controller: *silicon model of spinal cord circuits*
- Phase controller: *controlling Behavior*

**Future and Conclusion**
- High degree of freedom prosthetic limbs
- Sensory feedback and haptics
Learning from Nature to Make Machines See
Visual Processing in Humans

MT
Retina = Camera
LGN = “Relay”
Visual Cortex:
Shape, Color, Object, Motion, Stereo Vision

After wikipedia.com
Front-End of Vision System: Photoreception in the Retina

Rods and Cones

Source unknown
Conventional CMOS Cameras: Integrative Photo-detection

150 million sold in 2004, 55% annual growth rate to >700 million by 2008

Power consumption is relatively low (~ 10’s of mW for VGA)

2 Mega Pixels is probably the limit of usefulness

Download bandwidth is a problem (service providers would like more people to download their pictures)

There is a fear that it will represent the next technology bubble .... So much hype, legal problems ...

Small (~ 100 x 100 pixels) imagers, with smarts (e.g. motion, color processing) have market in toys, sensor networks, computer optical mouse ...
Conventional CMOS Cameras:
Voltage Mode Active Pixel Camera

Integrative Imagers:
Voltage domain; Dense arrays; Low Noise;
Low dynamic range, Not ideal for computation

Simple APS: Fossum, 1992
Current Active Pixel Sensor

Integrating Current output

\( V_{\text{reset}} \leq V_{DD} - |V_{tP}| \)

\( V_{col} \approx V_{DD} - 0.2V \)

\[
I_{\text{pix}} \approx \frac{W_2}{L_2} k_p (V_{DD} - |V_{tP}| - V_{\text{pix}}) (V_{DD} - V_{col})
\]

\[
I_{\text{pix}} \propto -V_{\text{pix}} (V_{DD} - V_{col})
\]

\[
I_{\text{pix}} \propto -V_{\text{pix}} \propto \text{Light} \times \text{Time}
\]

Philipp et al, 2008
Improved Current Mode Photodetection

Image quality has been improved
Non-linearity due to mobility degradation degrades performance under bright light

Philipp et al, 2008
Spike-Based CMOS Cameras: Octopus

Imaging Concept

Sample Image

Other approaches:
- J. Harris, “Time to first Spike,” 2002

Culurciello, Etienne-Cummings & Boahen, 2003
APS-Based Difference Imagers
On-Set and Off-Set Imaging

Narrow Rejection Band

Chi et al., 2007
Color Processing: RGB to HSI: Why?

Desaturated Color

Saturated Color

White

Blue

Red

Green

Black

Additive shift

Multiplicative shift

\[ r = I_{\text{bias}} \frac{R}{R + G + B}; g = I_{\text{bias}} \frac{G}{R + G + B}; b = I_{\text{bias}} \frac{B}{R + G + B} \]

\[ \text{Sat}(R, G, B) = I_{\text{bias}}[1 - \min(r, g, b)] \]

\[ \text{Hue}(R, G, B) = \arctan(X / Y) = \arctan\left( \frac{0.866(G - B)}{2R - G - B} \right) \]

Etienne-Cummings et al., 2002
Examples: Chroma-Based Object Identification

Skin Identification

“Learned” templates

Fruit Identification

Etienne-Cummings et al., 2002
Coke or Pepsi?

Etienne-Cummings et al., 2002

\[ SAD = \sum_{\Theta} |I_{i,j} - T_{i,j,k}| < \lambda_k \]
Single-chip stereo (3D) vision system

For use in:

- Autonomous systems
- Vehicle navigation
- Man-machine interfaces

Requirements

- Fully integrated
- Digital output
- Low power

Replaced with

Philipp et al., 2006
Chip Architecture

- Vertical averaging
  - Select multiple rows

- Parallel computation

- SAD matching metric

- Loser-Take-All
  - Smallest SAD value

\[ SAD(x, y, d) = \sum_{i=x}^{x+14} \left| r_{sum}(i, y) - l_{sum}(i + d, y) \right| \]

\[ \Delta_x(x, y) = \arg\min_{d \in D} SAD(x, y, d) \]

Philipp et al., 2006
## Chip Characteristics

<table>
<thead>
<tr>
<th>Technology</th>
<th>0.35µm 4M2P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die Size</td>
<td>3.5mm x 3.3mm</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>10µm x 10µm</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>26%</td>
</tr>
<tr>
<td>Image FPN</td>
<td>1.2% (no CDS)</td>
</tr>
<tr>
<td>Imager Size</td>
<td>128 x 128 x 2</td>
</tr>
<tr>
<td>Depth Map Size</td>
<td>114 x 124</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>30fps (40fps max)</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>33.2mW (3.3V, 30fps)</td>
</tr>
</tbody>
</table>

*Philipp et al., 2006*
Results

Movie: 30fps @ 33.2mW
- Right imager output texture mapped to depth results
- Color (at lower right) corresponds to depth
- Note: Plateau under the tiger is a black table
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Learning from Nature to Robots
Walk
Central Pattern Generator (CPG)

- In the spinal cord of vertebrates
- Generate patterned outputs to activate muscles
- Motor systems with regular, periodic activity (breathing, chewing, locomotion, etc.)
- Architecture is preserved across species [Cohen et al., 1988]
- CPG is used for “periodic” not specialized, locomotion

Source: J. M. Cleese, MPFC, 1970
CPG Architecture

First conceptual “model” in 1911 by T. G. Brown: half-center oscillator

HCO structure preserved in modern models
Cellular models in primitive vertebrates
Models in higher vertebrates are less detailed; designed to match behavioral data

Source: Grillner, Nat Rev Neurosci, 2003
Source: Rybak et al., J Physiol, 2006
CPGs in Action

Source: Mellen et al., 1995; Grillner & Zangger, 1984; Dimitriavic & Minassian et al., 2004
Cat Walking

IF-THEN formulation of “rules” governing hind limb stepping in cats:

- **Stance-to-swing transitions:**
  - *IF* ipsilateral hip is extended
  - *AND* ipsilateral limb is unloaded
  - *AND* contralateral limb is bearing weight
  - *THEN* initiate flexion in the ipsilateral limb

- **Swing-to-stance transitions:**
  - *IF* ipsilateral hip is flexed
  - *THEN* initiate extension in the ipsilateral limb

Ekeberg and Pearson, J Neurophys, 2005

Saigal et al., 2004; Prochazka, 1996; Guevremont et al., 2007
Designing the Gait Controller’s CPG Network

- Patterns in normal walking and IF-THEN formulation provides basis for CPG network
- Incremental design process
  - Extensors and flexors in counterphase
  - Alternate between stance (extension) and swing (flexion) phases ~ 70-30 duty cycle
  - Stance to swing and vice-versa triggered by two main proprioceptive inputs
    - Hip angle
    - Ankle load
- Extensible: replace flexor and extensor neurons with hip/knee/ankle subpopulations
- Structure similar to biology-based models [Pearson, personal comm.]

Source: Vogelstein et al., *IEEE TBioCAS*, 2008
Hardware Development: Gait Controller

- Develop hardware system to prescribe motor output based on pre-defined gait and current sensorimotor state
- Need to know what the biological CPG is doing at all times and what we want it to do next in order to effectively control it
- Build a silicon model of biological CPG, i.e. a neuromorphic silicon CPG chip (SiCPG)

CPGv2 (Tenore et al., 2004)  
CPGv3 (Tenore et al., 2006)
Which Neuron Model?

Making a Robot Walk with CPG Chip

- Use artificial motor system to develop on-line phase control infrastructure

Materials:
- Partially-supported bipedal robot ("RedBot") or RoboCat
- Reconfigurable silicon CPG chip
  - CPG controls hip movements, knee/ankles are passive

Lewis et al., 2005; Russell, Orchard et al, 2007
When Coupling Goes Good & Bad

Baby Steps

Strauss

Night on Town

Hurdles
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Restoring Function to the Impaired
Spinal Cord Injury (SCI)

- SCI is usually a focal injury: vertebral body dislocation → spinal cord contusion
  - Kills spinal cord cells at lesion site
  - Severs connections
  - Leaves cells above/below lesion intact
- In most cases (~65%), lower limb CPG is intact after SCI
- Paralysis is caused by loss of descending control of the CPG, not by loss of CPG itself
  - Tonic & phasic inputs to CPG are disconnected
  - Efferent inputs required to activate CPG and control locomotion
  - Paralysis
Responsibilities of Locomotion Controller

1. **Select Gait**
   + specify desired motor output
     - phase relationships
     - joint angles

2. **Activate CPG**
   + tonic stimulation initiates locomotion
     - epidural spinal cord stimulation (ESCS)
     - intraspinal microstimulation (ISMS)

3. **Generate “Efferent Copy”**
   + monitor sensorimotor state
     - external sensors on limbs
     - internal afferent recordings

4. **Control Output of CPG**
   + phasic stimulation
     (efferent copy required for precisely-timed stimuli)
     - convert baseline CPG activity into functional motor output
     - correct deviations
     - adjust individual components
     - adapt output to environment

*Vogelstein et al., 2008*
12 pairs of IM electrodes: 3 each for left/right hip, knee, and ankle extensors/flexors

Two types of sensory data were collected for each leg
- Hip angle (HA)
- Ground reaction force (GRF)

Source: Vogelstein et al., IEEE TBioCAS, (submitted)
Results: SiCPG Chip Controls Locomotion in a Paralyzed Cat

Vogelstein et al., 2008
Results: SiCPG Chip Controls Locomotion in a Paralyzed Cat

We have also shown that turning control is possible using phasic stimulation of biological CPG

- Use error between desired activity = “efferent copy” and measured activity to stimulate spine

Vogelstein et al., 2008
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Control paradigm

- Acquisition of electrophysiological signals involved in generation of movement
- Extraction of movement-related information from biosignals
- Provide sensory information to the nervous system
State-of-the-art of Prosthetic Hands

JHU/APL RP2009 Prototype II Hand
Repetitive movements: Hand opening/closing

Tenore et al., 2008
Experimental protocol

- Acquisition of non-invasive surface EMG signals from forearm (and upper arm)
- Subjects perform finger and hand movements on cue (audiovisual) – 18 total
- Transradial amputees perform movements also with intact hand simultaneously

Tenore et al., 2007
Results

- 4 subjects, 12 movements
  - 32 electrodes able-bodied subjects,
  - 19 electrodes on transradial amputee
- Confusion matrices: allow identification of misclassified movements
- Transradial amputee is?

Tenore et al., 2008
Visualization on Virtual Integration Environment

- VIE provided by JHUAPL for fast prototyping of decoding algorithms
- VIE in action
- Real Time Decoding

Tenore et al., 2008
Conclusions and Future

Fully neurally integrated prosthetics

- **Thoughts** to action (decoding of intent)
- Sensors to **feeling** (encoding of reaction)
- **Knowing** where is the limb (representing joint space)

Lucas Films, 1978
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