The Origins of BMI
(Brain-Machine Interfaces)

Joseph Gengerelli, UCLA (1950s)

Jose Delgado, Yale (1970s)
Mind Out of Body: Controlling Machines with Thought

In an exclusive excerpt from his new book, a pioneering neuroscientist argues that brain-wave control of machines will allow the paralyzed to walk, and portends a future of mind melds and thought downloads.

Scientific American, February 2011

“Almost every time one of my scientific manuscripts returned from the mandatory peer-review process during the past three decades, I had to cope with the inevitable recommendation that all scraps of speculative thinking about our ability to interface brains and machines should be removed from the papers …”

[Beyond Boundaries: The New Neuroscience of Connecting Brains with Machines—and How It Will Change Our Lives, by Miguel Nicolelis]
Learning about the operational mechanisms of the brain

- Only marginally understood
- Potential benefits to humanity hard to overestimate
  - Health care
  - Improved interfaces
- Could have huge impact in totally different domains (e.g. neuro-inspired computation)

The Decade of Neuroscience?
Deafness (cochlear implant)
- ~250 million deaf people worldwide, 2/3 in developing countries
- > 100,000 cochlear implant users worldwide
- 22,000 adults and 15,000 children live in the US
- Cost: US$ 40-60K

Deep brain stimulation (BDS)
- Disease: Movement Disorders (Parkinson’s Disease, Tremor)
- Market Size: Millions
- Approved in 1997
- 80,000 implants total worldwide
- Cost: US$ 50,000

[Sources: National Institutes of Health, Neurology journal]
Original idea launched by Carver Mead in the 1980’s
Active research area with human trials under way ...
But … turned out harder than originally expected!

Maybe look at neural signaling before stimulation!

[ Pictures courtesy of J. Wyatt and the Boston Retinal Implant Project]
BMI for Motor Control

- **Spinal cord injuries/amputees (upper-limb prosthesis)**
  - Estimated population (US) of 200,000 people
  - 11,000 new cases in the US every year

The BMI Spectrum

[Schwartz et al. Neuron, 2006]
Towards Integrated BMI Interface Nodes

Illustration art: Subbu Venkatraman

* “Michigan” and “Utah” Electrode Arrays shown
Goal of BMI Interfaces:
Acquire and Transmit Neural Signals Reliably and Consistently Over Long Lifespans (> 10 Years)

Challenges: Weak signal, Low SNR, High Offset, Mixture of field potentials and action potentials
Why Extreme Miniaturization?

- Resolution – observations at the cellular level
  - Need spatial measurement resolutions on the scale of 100 μm

[Pictures courtesy of T. Blanche, UCB]

- Reliability and longevity
  - Scarring reduces sensitivity and cause failure
  - Maybe addressed by “truly untethered” free-floating nodes
Miniaturization - It’s All About Energy!

- **Batteries**
  - problems:
    - size
    - replacement

- **Energy scavenging inside the body**
  - a relatively young research area
  - e.g. utilizing body heat (thermoelectric)
    - 0.6 µW / mm² @ ΔT=5°
    [Paradiso05]

- **Powering via RF**
  - advantages:
    - energy source sits outside the body
    - versatile
  - limitations:
    - possible health risks of EM radiation
Attractive Option: Glucose Biofuel Cell

Glucose Oxidation

O=O

+ catalyst

glucose

gluconic acid

dos as the body does” – Turn natural sugars into energy

Example:

State-of-the-art:

<table>
<thead>
<tr>
<th>in-vitro experiments (non-physiological conditions)</th>
<th>in-vitro experiments (near physiological conditions)</th>
<th>in-vivo experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.6 - 165 μW/cm²</td>
<td>2 - 55 μW/cm²</td>
<td>2.2 - 70 μW/cm²</td>
</tr>
</tbody>
</table>

RF Harvesting – State-of-the-Art

<table>
<thead>
<tr>
<th>Reference</th>
<th>[Yu03]</th>
<th>[Harrison07b]</th>
<th>[O’Driscoll09]</th>
<th>[Xiao10]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implanted Antenna</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size [mm x mm]</td>
<td>not stated</td>
<td>5 x 5</td>
<td>2 x 2</td>
<td>10 x 15</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>4</td>
<td>2.64</td>
<td>915</td>
<td>915</td>
</tr>
<tr>
<td>Link Parameters</td>
<td>10 mm air</td>
<td>10 mm air</td>
<td>15 mm bovine muscle</td>
<td>not stated</td>
</tr>
<tr>
<td>Transmit Power [mW]</td>
<td>2100</td>
<td>not explicitly stated</td>
<td>250</td>
<td>not stated</td>
</tr>
<tr>
<td>Received Power [μW]</td>
<td>22900</td>
<td>13400</td>
<td>200</td>
<td>160</td>
</tr>
<tr>
<td>Minimum Input Amplitude [V]</td>
<td>5.6</td>
<td>3.55</td>
<td>0.7</td>
<td>0.125</td>
</tr>
<tr>
<td>Power Available for Electronics [μW]</td>
<td>20700</td>
<td>10800</td>
<td>140</td>
<td>20</td>
</tr>
</tbody>
</table>

Need to take into account:
- Real transmission channel (tissue, fat, bone)
- Health considerations and regulations
Wireless Power and Size

- Specific absorption rate (SAR) sets the limit on external power
- Thermal considerations limit power dissipated by implant
- Available power drops with size by $d^4$ or more

Power Available at Matched Input Terminal

Ultra Low-Power Design Essential!

[Rabaey, Mark, et al., DATE 2011]
Key Concepts of Ultra-Low Power BMI Nodes

- Efficiency - Every electron counts
- Exploit technology scaling
- Operate at the lowest possible voltages!
- Rethink computational and communication paradigms
- Innovate and think out-of-the-box!
Efficiency:
Maximizing Power that can be Applied

- **Externally applied power** limited by health concerns
- Limit set by Specific Absorption Rate (SAR)
- **1.6 W/kg averaged over 1 g of tissue (in US)**

\[
\text{SAR} = \frac{\sigma |E|^2}{\rho}
\]

Segmented transmit loop increases power available to the implant by 47% (at 500 MHz)

[Mark, Bjorninen et al., Biowireless 2011]
Efficiency – Optimization of RX Antenna Size and Frequency

Maximum Achievable Gain vs. Frequency

Simulations (HFSS) match in-vivo measurements

(shown for a single turn 1 mm x 1 mm implanted antenna)
Boosting the Rectifier Efficiency

At 500 MHz for 1mm antenna
Max input voltage: 145 mV

Solution:
Pulsed power transmission
Keeps average SAR while increasing efficiency by 25%
Proof of Concept:
1 mm$^3$ Wirelessly-Powered Node

Delivers 26 uW or 8 uW of power (IEEE, FCC)

1 cm of skin, fat, bone

[Mark, Chen, et al., VLSI 2011]
Riding the Technology Wave?

Power and Area of minimally-invasive devices dominated by analog front-end:
- Ultra-low noise
- Offset cancelation
- Low frequency signal separation

C_{in} = 5-20pF

Eliminate passives to reduce area
Technology Scaling a Must!

A 0.013mm², 5uW DC Coupled Neural Signal Acquisition IC with 0.5V Supply

- Digital transistors are cheap in advanced CMOS processes
- Avoid large capacitances by dc-coupling and filtering in digital domain
- No high-precision analog components

[R. Muller et al, ISSCC 2011]
Scaling the Supply Voltage
Digital processing to reduce data rate and improve reliability

Example: Spike extraction

Courtesy: Dejan Markovic [UCLA]
Ultra Low-Voltage Design

Self-timed implementation reduces leakage and impact of variability at 0.25 V

Power consumption (µW) @ 0.2V

- Synchronous Static CMOS: 0.46
- Self-timed DCVSL: 0.12
- 74% reduction

- 0.25 µW/channel @ 0.25V
- 0.03mm² in 65nm CMOS

[Courtesy: TT. Liu, UCB]
Innovative Communication Architectures

Wireless data transmission at minimal energy/bit and footprint

- Take advantage of wireless powering using RFID-style techniques
- Increase data rate by using impulse-based modulation
- Reflective Impulse Radio: 2 Mbits/sec, 300 fJ/bit, ~0.01 mm²

[Mark, Chen, et al., VLSI 2011]
Putting it all Together – “Neural Dust”

- Thousands of “sensing nodes” freely embedded in neo-cortex
- Interrogated by array of nodes located on neo-cortex surface
- Communicating with and powered by ex-cranial interfaces

[Courtesy: W. Biederman and D. Yeager, UCB]
Neural Dust - Thinking Out-of-the-Box

- Current neural acquisition systems measure voltage signals
- Neural signaling is electrochemical process
- Why not measure changes in chemical concentrations (e.g. potassium ions) and translate into electrically observable signals

[Courtesy: M. Maharbiz]
Exploring Alternatives Routes: μECoG

2006 2011

[Courtesy: P. Ledochowitsch, R. Muller]
Fabricating μECoG Arrays

1. Carrier wafer cleaning
2. Parylene deposition (~ 9 μm)
3. Metal lift-off (Cr/Au/Pt, 250 nm total)
4. Parylene deposition (~ 1 μm)
5. Photoresist etch mask
6. Parylene etching and resist removal
7. Device release from carrier

Repeat for each metal layer

ASICs can be directly ACF bonded to device – providing structural and electrical integrity

μECoG on Macaque motor cortex (48 channels, 0.8 mm pitch)

[Courtesy: P. Ledochowitsch, M. Mabarbiz]
Wireless μECoG may provide up to 1000 channels with pitch as low as 200 μm.
- Providing unprecedented resolution and offering huge potential for BMI (ALS, Epilepsy).
- Antenna printed on polymer substrate

Circuit elements similar to AP sensor nodes

[Courtesy: P. Ledocowich, R. Muller, M. Maharbiz, J. Rabaey]
An Integrated (Long-Term) Vision: Combining “Neural Dust” and μECoG

“An implanted neural interface that can provide imaging of neural activity at multiple scales of resolution using arrays of patterned and free-floating sensors”
“The combination of genetic and optical methods to control specific events in targeted cells of living tissue, even within freely moving mammals and other animals, at the high speeds (millisecond-timescale) needed to understand brain information processing. - Wikipedia”

Leading effort:
K. Deisseroth,
Stanford
Final Reflections ....

- Brain-Machine Interfaces the ultimate in immersive technologies
  - The potential is huge - Societal impact first, human advancement next
- ULP circuit and systems design in concert with innovative technologies to provide “cellular electronics”
- “It’s the System … Stupid!”
  - It is not the brain alone
  - Explore, analyze, and implement advanced closed-loop learning systems
- Requires broad multi-disciplinary collaboration
  - The new reality of engineering
  - A major attraction to a new generation of engineers and beyond
Some Musings Going Forward

- BMI: an example of the many “nanomorphic” bio-interfaces we may see emerging over the coming decades

“The Nanomorphic Cell is a conception of an atomic-level, integrated, self-sustaining microsystem with five main functions: internal energy supply, sensing, actuation, computation and communication” [REF: Wikipedia]

- Potential target: observing living cells in vitro

- Even further breakthroughs in size and energy reduction needed

- Opportunity: nano-technology

Other readings: M. Crighton, N. Stephenson
Kiitos - Thank you!

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