Brain-Machine-Brain Interfaces for Massively Parallel Neurorecording and Microstimulation

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Polystim Neurotechnologies

Outline

◆ Motivation
  ▪ Brain-Machine-Brain Interfaces
  ▪ Implantable Neuroprostheses

◆ Multichannel Neurorecording
  ▪ Acquisition, and Compression
  ▪ Spike Detection : Analog/Digital Techniques
  ▪ Thresholding : Conventional, and Adaptive
  ▪ Energy Delivery, and Data Transmission
  ▪ Electrodes, Integration, Assembly and Validation
  ▪ Prototyping and Case Studies

◆ Laboratory-on-Chip based Sensors
  ▪ Neurotransmitters manipulation and characterization

◆ Resources/Summary
Massively Parallel Neurorecording: Mixed-Signal Blocks

- Input-ref. noise: 5.6 μVrms, Power consumption: 9 μW

Analog Biopotential Detector

- Sub-microwatt biopotential detector based on a custom analog processor
- Enhances biopotentials for detectability and captures complete waveforms

**Diagram:**

1. **Input AP waveform**
   - AP duration ≈ 2 ms

2. **Pre-processor output**
   - Detection point
   - Threshold value ($V_{THR}$)

3. **Decision block output**
   - $V_{LOW}$
   - Detection window

4. **Delayed AP waveform**
   - $T_d$
   - AP duration ≈ 2 ms

Mathematical representation:

- $V_{in}(t)$
- $V_{in}(t-T_d)$
- $V_{THR}$
- $V_{COMP}$
- $V_{HIGH}$
- $V_{LOW}$
- $t_1$, $t_2$, $t_3$, $t_4$
Gm-C based Analog pre-processor. The Teager energy operator (TEO):

$$\psi(x(t)) = \left( \frac{dx(t)}{dt} \right)^2 - x(t) \left( \frac{d^2 x(t)}{dt^2} \right).$$

Delay element: 9th-order allpass delay filter

Decision block: Latched-comparator
**Experimental Results: Analog Biopotential Detection**

- Implemented in a CMOS 0.18-µm, it measures **272x257 µm²**.
- Detector + delay filter: ultra-low-power dissipation of **780 nW**: validated with synthetic neural waveforms.
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Statistical SP (Cont’d) : Adaptive Spike Detection

- Neural signals are not stationary, and simultaneous recording is required: Setting the detection threshold adaptively and automatically is crucial.

- Various spike detectors have been developed (Matching filter, optimal filter, wavelets, etc.)

- The TEO is a powerful tool: it requires no prior knowledge about spike shapes, and present a good trade-off between the probability of detection ($P_D$) and the probability of false alarm ($P_{FA}$).

- The definition of the discrete-time TEO is given by:

  $$\psi [x(n)] = x^2(n) - x(n+1)x(n-1)$$

- $E\{\psi[.]\}$ can serve as an indicator to detect the presence of spikes, where $E\{\cdot\}$ is the expectation operator.

- To estimate $E\{\psi[.]\}$ the smoothed-TEO (STEO) $\psi_s[x(n)]$ is introduced as

  $$\psi_s [x(n)] = w(n) \ast \psi [x(n)]$$

  $$\psi_s [x(n)] = \sum_{k=0}^{L-1} w(k) \psi [x(n-k)]$$

$\psi_s[x(n)]$ is the test statistic
Statistical SP (Cont’d) : Adaptive Spike Detection

- This detection can be formulated as a **binary** hypothesis testing:

  \[ H_0 : x(n) = b(n) \quad n=0,1,2,... \]

  \[ H_1 : x(n) = s(n) + b(n) \quad n=0,1,2,... \]

  where \( H_0 \) and \( H_1 \) are the null and alternative hypotheses.

- A spike is present if \( \psi_s[x(n)] > T \); otherwise the signal is only noise.

- To set \( T \) of \( \psi_s[x(n)] \), the probability density function (pdf) under the null hypothesis \( H_0 \) has to be known **a priori**.

- As the TEO is a nonlinear operator, the pdf cannot be evaluated in a **closed-form**. Then a **direct parametric approach** is introduced, where only noise is present at the input and a multiplier \( p \) depends on \( P_{FA} \)

\[
T = \mu + p\sigma ; \quad \mu \text{ and } \sigma \text{ are statistical moments}
\]

- Setting \( T \) this way assumes that no spike is present, so the estimation of \( \mu \) and \( \sigma \) can therefore be unbiased by the presence of spikes.
Statistical SP (Cont’d) : Adaptive Spike Detection

- In statistics, spikes are considered in this case as outliers. So, robust statistic methods are used to estimate $\mu$ and $\sigma$.

**Determination of $\mu$ of $\psi_s[x(n)]$**

$$\mu_{\psi_s} = E\{\psi_s[x(n)]\} = E \{ \sum_{k=0}^{L-1} w(k) \psi [ x(n-k) ] \}$$

$$= \sum_{k=0}^{L-1} w(k) E\{ \psi [ x(n-k) ] \}$$

$$\mu_{\psi_s} = 2.24(r_{xx}(0) - r_{xx}(2))$$

**Determination of $\sigma$ of $\psi_s[x(n)]$**

$$\sigma_{\psi_s}^2 = var\{\psi_s[x(n)]\} = E\{\psi_s^2[x(n)]\} - E^2\{\psi_s[x(n)]\}$$

$$= E\{\psi_s^2[x(n)]\} - \mu_{\psi_s}^2$$

$$\sigma_{\psi_s}^2 \approx 4.8r_{xx}^2(0) + 0.7r_{xx}^2(1) + 4.4r_{xx}^2(2) + 0.6r_{xx}^2(3) - 9.3r_{xx}(0)r_{xx}(2) - 1.2r_{xx}(1)r_{xx}(3)$$

where $r_{xx}(m)$ is the autocorrelation of $x(n)$ at lag $m$.

- Both $\mu_{\psi_s}$ and $\sigma_{\psi_s}$ depend on the autocorrelation function of the neural signal $x(n)$.

- Autocorrelation function is sensitive to additive outliers (spikes) in the signal.

- Noise only cannot be separated from spikes, the use of an autocorrelation estimator, robust to the presence of additive outliers in $x(n)$, is crucial.

Robust statistics give estimators that are not affected by outliers.

Few approaches to obtain a robust covariance/correlation estimator are available. We choose the highly robust estimation of the autocorrelation based on a scale approach, by means of the following identity:

\[ r_{xx}(m) = 0.25 \left[ \text{var}\{x+x_m\} - \text{var}\{x-x_m\} \right] \]

for a Wide-Sense Stationary process, the autocorrelation is applied on the random process \( x \) with a delayed \( x \) with a lag \( m \).

\( r_{xx}(m) \) results from the estimation of the variance. Hence, a robust estimator of the variance is necessary.

\( Qn \)-scale estimator is a robust variance estimator especially under the Gaussian distribution. It is defined by:

\[ Qn\{x\} = \lambda \left[ \text{abs}\{x_i - x_j\}; i < j; i,j = 1,2,...N \right]^{(k)} \]

where \( \text{abs}\{.\} \) is the absolute value operator, \( N \) is the number of samples used to calculate \( Qn \), factor \( \lambda \) at the Gaussian distribution case is equal to 2.2191, and \( (k) \) represents the \( k \)-th order statistic.
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◆ Resources/Summary
Inductive Power and Data Links

**Inductive Data Links : Integrated BPSK/QPSK**

BPSK Costas-loop

QPSK Demodulator

**BPSK**
- CMOS 0.18µm
- 13.56 MHz
- 1.6* Mbps*
- 1.2* Mbps**
- 0.61 mW**

**QPSK**
- CMOS 0.18µm
- 13.56 MHz
- >10* Mbps
- 8.0** Mbps
- ~1.0 mW**

*Postlayout;  **Measured
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Epileptic Seizure: Analysis

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Kansai Chapter, 2012

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Neurotransmitters Detection and Manipulation

Sensing electrodes: capacitive sensor\(^1\)

Output signal proportional to liquid concentration

DEP force

CMOS chip\(^2\)

Acquisition module: CBCM technique

Actuation electrode matrix

Two 180° dephased AC signals

CMOS chip\(^2\)

0.18 μm CMOS modules

Actuation module: Frequency and amplitude control
Charge-Based Capacitor Measurement (CBCM)

- Adjustable current mirror gain (D1-Dm)
- Sensing capacitances values for different analytes;
- Different parasitic capacitances of different chip samples.

\[ I_{S} - I_{R} = f \ Vdd \ (C_{R} - C_{0}) \]

\[ I_{R} = I_{R0} \ (1 + 2^{m-1}D_{C1} + \ldots + 2^{m-k}D_{Ck} + \ldots + D_{CM}). \]
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NEWCAS 2012
10th IEEE International NEWCAS conference
June 17 - 20, 2012, Montréal, Canada
Summary

☑ Multi-Channel Intracortical biosensing
☑ Adaptive Thresholding and automatique spike detection
☑ Epilepsy seizures onset detection
☑ LoC-Based neurotransmitter detection

Design challenges are multidimensional

☐ Data Compression : CS technique
☐ Microwatts Wireless : WuRx
☐ Fast data transmission : ~ 50 Mb/s
☐ Harvesting & scavenging energy : ~ 25 mW
☐ Small size & low weight;
☐ Low-power spike detection, sorting & decoding algorithms is needed

Important facts

☐ Transition to clinical use must be accomplished with minimal assistance.
☐ BMI systems must be safe, not to generate undesired actions.
Acknowledgment

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Thank You

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