Implantable and Wearable Microelectronic Devices to Improve the Quality of Life for People with Disabilities

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Motivation

• Healthy People 2020: 54 million Americans (~20%) living with disabilities and the number is on the rise especially among elderly (Age 65+).

• 11,000 cases of severe Spinal cord injury (SCI) per year add to a total population of ~250,000.

• 55% of SCI victims are 16~30 years old, who will need lifelong special care services.

• Most of these individuals experience a poor quality of life.

**Advanced technology development to improve the quality of life for individuals with the most severe disabilities.**

<table>
<thead>
<tr>
<th>Injury or Disease</th>
<th>Population</th>
<th>Annual Incidence in USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paralysis of extremities</td>
<td>2,000,000</td>
<td>N/A</td>
</tr>
<tr>
<td>Severe spinal cord injuries</td>
<td>250,000</td>
<td>11,000</td>
</tr>
<tr>
<td>Effects of stroke</td>
<td>4,000,000</td>
<td>600,000</td>
</tr>
<tr>
<td>Multiple sclerosis</td>
<td>350,000</td>
<td>N/A</td>
</tr>
<tr>
<td>Cerebral palsy</td>
<td>500,000</td>
<td>~10,000</td>
</tr>
<tr>
<td>ALS</td>
<td>30,000</td>
<td>5,600</td>
</tr>
</tbody>
</table>
Outline

**Implantable Microelectronic Devices (IMD)**
- Efficient power and wideband data transmission
- Wireless Integrated Neural Recording (WINeR) system
- Switch-Capacitor based Stimulating (SCS) system

**Modern Assistive and Rehabilitation Technologies**
- **Tongue Drive System (TDS)**: A wireless and wearable Brain-Tongue-Computer Interface
- TDS Hand Mentor Exoskeleton
- Tongue Tracking System (TTS)

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**Highly Efficient Inductive Power Transmission**

- **Battery powered devices:**
  - Low stimulus pulse rate
  - Autonomous (after initial adjustments)
  - Small number of stimulating sites

- **Inductively powered devices:**
  - High current (Neuromuscular stimulators)
  - High stimulus rate (Cochlear implants)
  - Large number of sites (Visual prostheses)
  - All implants should be wireless.

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*Images and illustrations from various institutions: Advanced Bionics Corp., Second Sight Inc., Medtronic Corporation, University of Southern California, Alfred Mann Institute - USC.*
Transcutaneous Link Power Losses

- **$P_B$:** Power drained from battery
- **$P_S$:** Power delivered to the primary coil
- **$P_1$:** Transmitted power
- **$P_T$:** Power passed through the tissue
- **$P_2$:** Received power
- **$P_L$:** Power delivered to the load (implanted electronics)

**Inductive Power Transfer Efficiency**

\[ \eta_1 = \frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2} \]

\[ Q_L = \frac{1}{\omega L_2} \left( \frac{R_2}{R_L} + \frac{\omega L_2}{R_L} \right) = \frac{1}{R_2 \sqrt{L_2} + \frac{1}{\sqrt{C_2}} + \frac{1}{R_L \sqrt{C_2}}} \]

\[ \eta_L = \frac{Q_2^2 R_{S2}^2}{Q_2^2 R_{S2}^2 + R_L} \]

\[ \eta = \eta_1 \cdot \eta_L \]

Power efficiency is a strong function of the coupling coefficient ($k$) and quality factor ($Q$) of the external and implanted coils.
### 3-Coil Inductive Link

\[
\eta_{3\text{-coil}} = \frac{k_{23}^2 Q_s Q_l (k_{24}^2 Q_s Q_{4L}) + k_{24}^2 Q_s Q_{4L} Q_l}{\cos(\theta)(1+k_{24}^2 Q_s Q_{4L})\sqrt{A^2 + B^2}}
\]

- \[A = 1 + k_{23}^2 Q_s Q_3 + k_{34}^2 Q_s Q_{4L} + k_{24}^2 Q_s Q_{4L}\]
- \[B = 2Q_s Q_3 Q_{4L}k_{23}k_{34}k_{24}\]
- \[\theta = \tan^{-1}(B/A)\]

### PTE and PDL in 3-Coil Link

Maximizing PTE should not be at the cost of decreasing PDL.

\[
P_{2,3\text{-coil}} = \frac{V^2}{2R_s} \frac{(k_{23}^2 Q_s Q_l)(k_{24}^2 Q_s Q_{4L})}{(1+k_{23}^2 Q_s Q_3 + k_{34}^2 Q_s Q_{4L})^2} Q_l/Q_s
\]

The optimal design maximizes both PTE and PDL.

\[
k_{23,\text{PDL}} = \left(1 + k_{23}^2 Q_s Q_3\right)^{1/2}
\]

\[
k_{34,\text{PDL}} = \left(1 + k_{23}^2 Q_s Q_{4L}\right)^{1/2}
\]
4-Coil Inductive Link

- 4-Coil link adds an additional DoF for impedance matching on the source side.
- If $k_{12}$ is large, the reflected load onto $L_1$ increases dramatically, which helps maximize the PTE at the cost of reducing PDL.

$$\eta_{4\text{-coil}} = \frac{(k_{12}^2 Q_2 Q_4)(k_{34}^2 Q_3 Q_4)(k_{34}^2 Q_3 Q_4)}{[(1+k_{12}^2 Q_2 Q_4)(1+k_{34}^2 Q_3 Q_4)+k_{34}^2 Q_3 Q_4] L_1} \frac{O_{4L}}{O_{L}}.$$

PTE and PDL in 4-Coil Link

If $k_{12}$ is large enough, 4-coil can tolerate variations in coil separation ($k_{23}$) and maintain a large PTE.

$$P_{4\text{-coil}} = \frac{V^2}{2R_i} \times \frac{(k_{23}^2 Q_2 Q_3)(k_{43}^2 Q_3 Q_4)(k_{43}^2 Q_3 Q_4)}{[(1+k_{23}^2 Q_2 Q_3)(1+k_{43}^2 Q_3 Q_4)+k_{43}^2 Q_3 Q_4]^2} \frac{O_{4L}}{O_i}$$

$$k_{23,\text{PTE}} = \left(\frac{\sqrt{1+k_{23}^2 Q_2 Q_3} (1+k_{43}^2 Q_3 Q_4)}{Q_2 Q_3}\right)^{1/2}$$

$$k_{23,\text{PDL}} = \left(\frac{(1+k_{23}^2 Q_2 Q_3)(1+k_{43}^2 Q_3 Q_4)}{Q_2 Q_3}\right)^{1/2}$$

Small overlap between high PTE and PDL areas.
**New Figure of Merit (FoM) for Inductive Power Transmission Links**

- **Trade-offs between high** PTE and sufficient PDL
- **High** PTE to reduce:
  - Reduce heat dissipation
  - Tissue exposure to magnetic field (safety)
  - Interference with nearby electronics (FCC)
- **Sufficient** PDL to:
  - Small PA transistors
  - Reduce Vs (safety)

\[
FoM = \frac{\eta_{\text{m-coil}}^n \times P_{\text{L,m-coil}}}{V_s^2}
\]

\[n = 0 \rightarrow FoM \equiv PDL\]
\[n \rightarrow \infty \rightarrow FoM \equiv PTE\]
### Wideband Transcutaneous Back Telemetry (Uplink)

- **Actuator & DSP**
- **Rx**
- **Skin**
- **Tx**
- **Nervous System**

- Invasive BCI
- Neural recording

*Images courtesy of Maysam Ghovanloo*

### Wideband Transcutaneous Forward Telemetry (Downlink)

- **Artificial Sensor**
- **Tx**
- **Skin**
- **Rx**
- **Nervous System**

- Wideband and robust forward telemetry links are needed for sensory substitute neuroprostheses such as retinal implants and cochlear implants
- Limited space and power available to the IMD for establishing a wideband and robust connection to the outside world

*Images courtesy of Maysam Ghovanloo*
**Power Carrier Freq. as Low as Possible**

- Carrier frequency should be below the coil self resonance frequency.
- More power loss in the power transmission and conditioning circuitry at higher frequencies.
- $0.1 \text{ MHz} < \text{Carrier Freq.} < 20 \text{ MHz}$
  Average density of electromagnetic power absorption in tissue increases as $f^2$.
- Tissue is more transparent to EM field at lower frequencies.
- Carrier Frequency $\uparrow \Rightarrow$ Penetration Depth $\downarrow$

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**Wireless Link Using Multiple Carriers**

- Low frequency for power transmission ($125 \text{ kHz} \sim 20 \text{ MHz}$)
- Medium frequency for forward data transmission ($50 \sim 100 \text{ MHz}$)
- High frequency for back telemetry ($0.4 \sim 2.4 \text{ GHz}$)
Minimizing Interference between Power and Data Carriers

Vertical coils
Shifted coplanar coils
Coaxial coils

Figure-8 coils

Carrier Based vs. Pulse Based

- Near-field inductive coupling
  - ASK → Low data rate due to limitations in high order filter integration at low frequency end of RF
  - FSK, QPSK, DPSK → High power consumption due to carrier-based modulation
  - LSK → Reduction of the received power due to duty cycling of the power carrier
- Far-field radiation
  - IR-UWB → Commercial IR-UWB in 3.1-10.6 GHz is highly absorbable in water (tissue)

Replicate IR-UWB in the near-field
**Effect of Q-Factor in Pulse-Based Data Transmission**

- Tail of the oscillation $\propto e^{-\left(f_t t \frac{\pi}{Q^2}\right)}$

- $Q = \frac{f_t}{BW} \Rightarrow Q \uparrow \Rightarrow BW \downarrow$
- $\Rightarrow Noise \downarrow \Rightarrow SNR \uparrow$

\[ Q_2 = 44.8 \quad \text{and} \quad Q_2 = 4 \]

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**Pulse Harmonic Modulation (PHM)**

- First pulse initiates oscillation on the Rx side at the tuned frequency of $L_2C_2$-tank, $f_t$
- Second pulse suppresses the oscillation of the first pulse by being $180^\circ$ out of phase

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**Patent Pending**
**PHM Simulations in MATLAB**

- Initiation Pulse
- Suppression Pulse
- Primary Time Constant
- Secondary Time Constant
- Initiation Pulse Envelope
- Suppression Pulse Envelope

**PHM-Based Transceiver ASIC**

- **ON-Semi 0.5 μm Std. CMOS**
  - Transceiver layout area = 0.61 mm²
  - Supply voltage: 3.3V
  - Data rate: 10.2 Mbps
- **TSMC 0.35 μm Std. CMOS**
  - Transceiver layout area = 0.23 mm²
  - Supply voltage: 1.8V
  - Data rate: 20.0 Mbps

**PHM Test Setup**

<table>
<thead>
<tr>
<th>Coil (Fig-8)</th>
<th>Size (cm)</th>
<th>#Turns(n)</th>
<th>L (nH)</th>
<th>R (mΩ)</th>
<th>C_p (pF)</th>
<th>C_t (pF)</th>
<th>SRF (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_1 (TX)</td>
<td>1×1</td>
<td>2</td>
<td>105</td>
<td>85</td>
<td>2.1</td>
<td>-</td>
<td>338°</td>
</tr>
<tr>
<td>L_2 (RX)</td>
<td>1.5×1.5</td>
<td>2</td>
<td>230</td>
<td>180</td>
<td>3.2</td>
<td>24.1</td>
<td>184.5°</td>
</tr>
</tbody>
</table>

**Measurement Results**

<table>
<thead>
<tr>
<th></th>
<th>Without PHM</th>
<th>With PHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate</td>
<td>10.2 Mbps</td>
<td></td>
</tr>
</tbody>
</table>

Without PHM

With PHM

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Inanlou, Kiani, and Ghovanloo, JSSC 2011
PHM Benchmarking

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Modulation Scheme</th>
<th>Tx/Rx (cm)</th>
<th>Coils Distance (mm)</th>
<th>$f_r$ (MHz)</th>
<th>Data Rate (Mbps)</th>
<th>Rx Power (pJ/bit)</th>
<th>Rx $Q$ at low freq</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghovanloo 2004</td>
<td>pcFSK</td>
<td>2/1.2</td>
<td>5</td>
<td>5/10</td>
<td>2.5</td>
<td>N/A</td>
<td>N/A</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Sawan 2005</td>
<td>BPSK</td>
<td>3.5/2.7</td>
<td>15</td>
<td>10</td>
<td>1.12</td>
<td>N/A</td>
<td>N/A</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>W. Liu 2008</td>
<td>BPSK</td>
<td>N/A</td>
<td>10–15</td>
<td>20</td>
<td>2</td>
<td>N/A</td>
<td>N/A</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Sawan 2010</td>
<td>QPSK</td>
<td>1.2/1.2</td>
<td>5</td>
<td>13.56</td>
<td>4.16</td>
<td>N/A</td>
<td>65.6''</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>Sarpehkar 2008</td>
<td>LSK</td>
<td>3.5/3.5</td>
<td>20</td>
<td>25</td>
<td>2.8</td>
<td>35.7*</td>
<td>30</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>H. J. Yoo 2009</td>
<td>BPM''</td>
<td>1.5/1.5</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>2.9</td>
<td>15</td>
<td>N/A</td>
</tr>
<tr>
<td>Inanlou 2011</td>
<td>PHM</td>
<td>1/1.5</td>
<td>10</td>
<td>67.5</td>
<td>10.2</td>
<td>345</td>
<td>48</td>
<td>$6.3 \times 10^{-8}$</td>
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<tr>
<td>Kiani 2013</td>
<td>PHM</td>
<td>1/3</td>
<td>10</td>
<td>66.6</td>
<td>20</td>
<td>180</td>
<td>96</td>
<td>$8.7 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Pulse Delay Modulation (PDM) using a Dual-band Power/Data Link

- Pulse-Based data transmission using a separate data link
- Modulate the zero-crossings of the undesired power carrier across $L_4C_4$ with short decaying oscillations
- Increasing $R_4$ ($Q_4$) to facilitate decay of $L_4C_4$ oscillations
Pulse Delay Modulation (PDM)

- Two short pulses to coincide the power carrier interference zero-crossings across L₄C₄ for “1” bits
- Comparing power signal with delayed interference on L₄C₄

PDM Simulation in MATLAB

Shift in zero crossings = 2.5 ns
**PDM-based Transceiver Diagram**

- On-Chip Level Shifter
- PA
- Non-Overlapping Clock Generator
- Power Transmission
- Data Transmission
- Skin/Air
- Receiver (Rx)
- Passive Rectifier
- LDO
- Clock Recovery
- LC Driver
- Pulse Pattern Generator
- Transmitter (Tx)
- Parasitic capacitance
- CD
- PD
- PD PW
- Tx Clk
- Tx Data
- Rx Clk
- Rx-Data

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**PDM-based Transceiver ASIC**

- Fully on-chip power/data transceiver
- CMOS tech: TSMC 0.35-µm
- Transceiver die area = 4.8 mm²
- Nominal supply voltage = 1.8 V
- Operating freq. = 13.56 MHz
- Data rate = 13.56 Mbps
PDM Test Setup

- Power link: printed-spiral and wire-wound coils
- Data link: a pair of planar figure-8 coils on FR4 PCB

<table>
<thead>
<tr>
<th>Link</th>
<th>Coil</th>
<th>Size (mm)</th>
<th>#Turns</th>
<th>Line Width (mm)</th>
<th>L ( filmmH)</th>
<th>R (Ω)</th>
<th>f (MHz)</th>
<th>Q</th>
<th>SRF (MHz)</th>
<th>Mutual Coupling (kH) *10^-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>L₁₁</td>
<td>12 × 12</td>
<td>5</td>
<td>2</td>
<td>500</td>
<td>0.5</td>
<td>13.56</td>
<td>85.2</td>
<td>116</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>L₂₂</td>
<td>10 × 10</td>
<td>3</td>
<td>0.255</td>
<td>195</td>
<td>0.34</td>
<td>13.56</td>
<td>48.8</td>
<td>237</td>
<td>-</td>
</tr>
<tr>
<td>Data</td>
<td>L₃₃</td>
<td>30 × 30</td>
<td>1</td>
<td>1</td>
<td>165</td>
<td>0.48</td>
<td>50</td>
<td>108</td>
<td>255</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>L₄₄</td>
<td>10 × 10</td>
<td>1</td>
<td>0.4</td>
<td>56.8</td>
<td>0.44</td>
<td>50</td>
<td>40.5</td>
<td>550</td>
<td>6.4</td>
</tr>
</tbody>
</table>

*L₂₂* was an AWG30 wire-wound coil. From measurements at the operating frequency, f. Q₇ was reduced to 5 by adding R₀ = 100 Ω.

PDM Measurement Results

- Data rate = 13.56 Mbps
- Distance = 10 mm
- Data osc. freq. = 50 MHz
- Signal-interference ratio (SIR) = -18.5 dB
- Shift in zero crossings = 2.3 ns
- Power delivered to load (PDL) = 42 mW
PDM Measurement Results

- Data rate = 13.56 Mbps
- Distance = 10 mm
- SIR = -18.5 dB
- Bit error rate (BER) = $4.3 \times 10^{-7}$
**PDM Benchmarking**

- PDM advantages:
  - First inductively-powered pulse-based transceiver
  - Low data transmitter and receiver power consumption
  - Robustness against power carrier interference and Small die area

<table>
<thead>
<tr>
<th>Reference</th>
<th>Mod.</th>
<th>d (mm)</th>
<th>Data Carrier (MHz)</th>
<th>Power Carrier (MHz)</th>
<th>Data Rate (Mbps)</th>
<th>TxD/Rx Power (pW/bit)</th>
<th>CMOS Tech. (um)</th>
<th>SIR (dB)</th>
<th>Die Area (mm²) (Data Tx/Rx)</th>
<th>VDD (V)</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghovanloo, 2004</td>
<td>pFSK</td>
<td>5/10</td>
<td>5/10</td>
<td>2.5</td>
<td>-152</td>
<td>1.5</td>
<td>-</td>
<td>-0.29</td>
<td>5</td>
<td>10⁻³</td>
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<tr>
<td>Hu, 2005</td>
<td>BPSK</td>
<td>15</td>
<td>10</td>
<td>1.12</td>
<td>-625</td>
<td>0.18</td>
<td>-</td>
<td>-0.2</td>
<td>1.8</td>
<td>10⁻³</td>
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<tr>
<td>Mandal, 2008</td>
<td>LSK</td>
<td>20</td>
<td>25</td>
<td>2.8</td>
<td>35.7/1250</td>
<td>0.5</td>
<td>-</td>
<td>2.2/2.3</td>
<td>2.8</td>
<td>10⁻⁶</td>
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<tr>
<td>Rush, 2012</td>
<td>FSK</td>
<td>-5</td>
<td>5</td>
<td>1.25</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
<td>2.7</td>
<td>-</td>
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<td>Rush, 2012</td>
<td>BPSK</td>
<td>20</td>
<td>48</td>
<td>3</td>
<td>3</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
<td>2.3</td>
<td>10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>Simard, 2010</td>
<td>QPSK</td>
<td>5</td>
<td>13.56</td>
<td>1</td>
<td>4.16</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2×10⁻⁴</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Zhou, 2008</td>
<td>BPSK</td>
<td>15</td>
<td>20</td>
<td>2</td>
<td>-3100</td>
<td>0.35</td>
<td>-12</td>
<td>-4.4</td>
<td>4.5</td>
<td>10⁻⁶</td>
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<tr>
<td>Chen, 2013²</td>
<td>DPSK</td>
<td>20</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>0.18</td>
<td>-</td>
<td>-</td>
<td>1.8</td>
<td>10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>This Work</td>
<td>PDM</td>
<td>10</td>
<td>50</td>
<td>13.56</td>
<td>13.56</td>
<td>960/162</td>
<td>0.35</td>
<td>-18.5</td>
<td>0.34/0.37</td>
<td>1.8</td>
<td>4.3×10⁻⁷</td>
</tr>
</tbody>
</table>

¹ A 1st-order off-chip filter was used to improve SIR to -6 dB. ² Including pads. ²² Second-order filter was used to improve SIR. ²²² LSK is only used for uplink.

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**Tongue Drive System**

_A Brain-Tongue-Computer Interface for Environmental Control and Computer Access_
Invasive BCI for Clinical Use

Intracortical electrodes (Single Unit Recording)

Subdural electrodes (ECoG Recording)

Switch Based Systems

- Simple and relatively low cost
- Easy to use
- Requires limb movement
- Slow and cumbersome
- Inflexible

E-talk Speech Tablet

Voice activated switches

Grasp Switch

Microlight Switch

Sip-n-puff Switch

EMG Switch
**Why Using Tongue?**

- Along with mouth occupies the amount of sensory and motor cortex that rivals fingers and hand: sophisticated motor control capability evident in speech and ingestion
- Fast movement with many degrees of freedom (DoF). Very flexible
- Connected to brain by a cranial nerve: escapes even high level spinal cord injuries
- Noninvasive access to tongue is possible.
- Not afflicted by repetitive motion disorders
- Does not fatigue easily. Very low rate of perceived exertion
- Cosmetic advantage and privacy. It is all inside the mouth
- Not influenced by the position of the rest of the body
- Unlike BCIs does not need concentration.

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**Tongue Drive System (TDS)**

An array of magnetic sensors detect the magnetic field variations resulted from the movements of a small magnetic tracer attached to the tongue, and wirelessly send that information to a portable computer where these tongue movements are translated to user commands.
**Tongue Commands**

- Right
- Left
- R-click
- L-click
- Up
- Down
- Resting

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**Magnetic Tracer Attachment**

**Temporary attachment:**

- By *tissue adhesives* to test-drive the TDS

**Semi-permanent attachment:**

- By *magnetic tongue piercing* to use the TDS on a regular basis
After screening, participants receive a magnetic tongue piercing, recover for 4 weeks, and participate in a 6-week trial including one computer access and one wheelchair navigation session per week.

**Experimental Methods (Computer Access)**

- **Horizontal Tapping**
- **Vertical Tapping**
- **Center-out Tapping**
- **Multidirectional Tapping**

48 Targets

45 Targets
**Experimental Setup (Wheelchair Navigation)**

- Q6000 electric-powered wheelchair from Pride Mobility Inc.
- Subjects drove in a ~50m obstacle course using 3 driving strategies:
  - Unlatched
  - Latched
  - Semi-proportional

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**Tongue Drive System vs. Sip-and-Puff**

- Center-Out Tapping Task Over 6 Sessions
- Maze Navigation Task Over 6 Sessions

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Tongue Drive System vs. Sip-and-Puff

\[
ITR = \frac{1}{T} \left( \log_2 N + P \log_2 P + (1 - P) \log_2 \frac{1 - P}{N - 1} \right)
\]

\(N\): number of individual commands
\(N_{TDS}=6\), \(N_{SnP}=4\)

\(P\): System accuracy

\(T\): System response time

Wolpaw et al., Clinical Neurophysiology 2002

Tongue Drive System vs. Sip-and-Puff

Powered Wheelchair Control Task Over 6 Sessions

Subjects perform considerably better over time.

Intraoral Tongue Drive System (iTDS)

• Sensors, all the electronics, and a small rechargeable battery will be integrated in a comfortable dental retainer.
• Completely hidden from sight → Gives users more privacy and confidence
• More stability inside the mouth. Protected against external mechanical interference and possible damage.
iTDS Implementation

iTDS Block Diagram
**iTDS Wireless Universal Interface**

**iTDS Common Applications**

[ Computer Access ]

- iTDS can substitute mouse or touch-screen, enabling full PC, tablet, or smartphone access with tongue motion

[ Powered Wheelchair Control ]

- iTDS can substitute joystick to provide control over powered wheelchairs (Forward/Backward/Left/Right/Neutral-stop).
Substituting the Smartphone with Beagle Bone Black

To create a stand-alone TDS

iTDS Special Applications

- iTDS can be used where physical motion has been hindered by the environment or by nature of the task.
- iTDS allows tongue to be used as a human motor output, like hands and fingers. Like the 3rd arm.
**TDS + Head-Mount Display**

A Truly Wearable Computer

- Hands-free mode of access for wearable computers with head-mount displays and virtual reality glasses, e.g. Google GLASS

**A Silent Speech Recognizer/Synthesizer**

- Recognizing phonemes, words and sentences from the physical tongue motion during silent speech → Privacy
- Aphonia, weak voice, Laryngectomees

Collaboration with Thad Starner, GT
Conclusions

• We have developed basic building blocks for high performance implantable microelectronic devices (IMD), particularly in the analog, RF, and power management units.

• We are building invasive BCIs (wireless neural recording, stimulation, smart wireless cage) as an advanced set of tools for neuroscience and electrophysiology research on freely behaving small animal subjects.
Conclusions

• **Tongue Drive System** (TDS) is a wireless, wearable, and minimally invasive brain-tongue-computer interface (BTCI) that enables individuals with severe disabilities to access computers, drive wheelchairs, and control environments with their **voluntary tongue motion**.

• A **Multimodal TDS** (mTDS) is under development to capture any remaining abilities of the end users and give them more degrees of freedom and ease of use for various activities of daily living (ADL).

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