FAST VISUAL TARGET IDENTIFICATION
FOR LOW-COST BCI SPELLER

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OUTLINE

• What is the brain-computer interface?
• Research goal
• Previously developed wearable BCI device
• Proposed target identification algorithm
• Experimental results
• Further work – make our own hardware
• Conclusion
Brain-Computer Interface

- Brain-Computer Interface (BCI) - emerging communication channel for humans
BRAIN-COMPUTER INTERFACE

• Brain-Computer Interface (BCI) - emerging communication channel for humans

Invasive

Jan Scheuermann, DARPA

Non-invasive

Courtesy Georgia Tech BrainLAB

Samsung

Lyon Neuroscience Research Center, 2012
Brain-Computer Interface (BCI) - emerging communication channel for humans

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BCI Speller
Brain-Computer Interface (BCI) - emerging communication channel for humans

• Can help patients with paralysis communicate with other people (stroke, spinal cord injury, …)

• Using non-invasive electroencephalogram (EEG) → non-invasiveness, simple operation
**Steady-State Visual Evoked Potential**

- Information transfer through visual evoked potentials (VEPs)
  - SSVEP: EEG response to flickering visual stimulation at a specific frequency

![Diagram](image_url)

- Flickering target
- Visual response
- Signal processing

**VEP based BCI System**

- Analog Front-End
- Signal Acquisition
- Signal Analysis
  - Feature Extraction
  - Target Identification

- Command Output

*Note: This image includes a diagram illustrating the process of a VEP-based BCI system, showing the visual pathway, electrode placement, and signal processing steps.*
VISUAL TARGET IDENTIFICATION IN BCI SPELLER

- Information transfer through visual evoked potentials (VEPs)
  - SSVEP: EEG response to flickering visual stimulation at a specific frequency

Francois-Benoit Vialatte, 2009
**RESEARCH GOAL**

**Previous BCI speller system**

- Attaching many electrodes on the head
- Discomfort to wear
- Long preparation/setup time
- EEG signal processing in PC
- Need powerful computing resource

![Previous BCI speller system](image1)

**Goal: Wearable BCI speller system**

- BCI device with better wearability
  - Support on-device EEG processing
    - Based on Low-power MCU platform
  - Display device with [Bluetooth®](#)
    - Target character display: visual stimulus
    - On-line speller: Identified target display

![Wearable BCI speller system](image2)
WEARABLE BCI DEVICE PROTOTYPE

• Behind-the-ear type device
  • Single-channel EEG + Bluetooth 4.0
  • Target identification software on host PC (EEG data transfer through Bluetooth)
  • 24-bit resolution ADC chip (for performance evaluation)

Co-work with Seoul National University (SNU)
WEARABLE BCI DEVICE PROTOTYPE

• Behind-the-ear type device
  • Single-channel EEG + Bluetooth 4.0
  • Target identification software on host PC (EEG data transfer through Bluetooth)
  • 24-bit resolution ADC chip (for performance evaluation)

IRB (Institutional Review Board) approved
COMPARISON TO COMMERCIAL DEVICES

- Small size & low power
  - Comfortable
  - Long battery life

- High performance
  - Low noise
  - High resolution

- But…
  - Requires powerful computing PC

<table>
<thead>
<tr>
<th></th>
<th>This Work</th>
<th>Neuroscan</th>
<th>EMOTIV EPOC</th>
<th>Neurosync</th>
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<tr>
<td>Dimension (mm)</td>
<td>54 x 20 x 10</td>
<td>-</td>
<td>-</td>
<td>63 x 40 x 25</td>
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<tr>
<td>Weight (g)</td>
<td>14.3</td>
<td>-</td>
<td>104.3</td>
<td>43</td>
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<tr>
<td>Number of Ch.</td>
<td>1</td>
<td>64-512</td>
<td>14</td>
<td>1</td>
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<td>250 / 500</td>
<td>Up to 20,000</td>
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<tr>
<td>ADC reference (V)</td>
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<td>Adjustable</td>
<td>N/A</td>
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<td>Amplification (V/V)</td>
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<td>Dynamic range</td>
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<tr>
<td>Noise level (µVrms)</td>
<td>0.11</td>
<td>0.5</td>
<td>about 1</td>
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<tr>
<td>Resolution</td>
<td>24bit / 48.4nV</td>
<td>24bit / 3nV</td>
<td>14bit / 0.51µV</td>
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<td>Bandwidth (Hz)</td>
<td>1-35</td>
<td>DC-3,500</td>
<td>0.2-45</td>
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<td>Communication</td>
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<td>USB</td>
<td>2.4GHz</td>
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<tr>
<td>Power</td>
<td>Li-polymer</td>
<td>Wall power</td>
<td>Li-polymer</td>
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<tr>
<td>Power consumption</td>
<td>19 hour</td>
<td></td>
<td>12 hour</td>
<td>N/A</td>
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IMPROVEMENT DIRECTION OF PROTOTYPE DEVICE

• Not Enough SNR: Poor SSVEP quality at behind-the-ear position

• Not Enough Computing Power: Requires external computing device

• Not Enough Communication Speed
IMPROVEMENT DIRECTION OF PROTOTYPE DEVICE

• Not Enough SNR: Poor SSVEP quality at behind-the-ear position
  • Move the electrode to back of the head (occipital region, Oz)

• Not Enough Computing Power: Requires external computing device
  • Propose the target identification algorithm for low-cost MCU and small memory
  • Maintain the BCI speller performance with negligible accuracy loss

• Not Enough Communication Speed
  • Reduce the signal processing time especially the timing dependent procedures
TARGET IDENTIFICATION ALGORITHMS

• PSDA (Power Spectral Density Analysis)
  • For single-channel SSVEP target identification
  • Simple operation: FFT & find maximum index
  • Weak performance for low SNR (signal-to-noise) SSVEP signal

![Diagram of Single-Channel EEG](image)

- **Single-Channel EEG $X$**
- **FFT**
- **$|X|$**
- **Maximum value**
- **Target**
**TARGET IDENTIFICATION ALGORITHMS**

- **Standard-CCA (Canonical Correlation Analysis)**
  - Correlation between EEG signal $X$ and reference sinusoidal signal $Y$ for each frequency
  - Should be computed for each target frequency $\rightarrow$ Maximum correlation: target

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*Z. Lin et al., “Frequency Recognition Based on Canonical Correlation Analysis for SSVEP-Based BCIs”, IEEE TBME, 2007*
**Target Identification Algorithms**

- Combination-CCA (Comb-CCA)*

- User-specific target identification using training data → more accurate!

- Uses three datasets
  - $X$: Input SSVEP signal set
  - $\bar{X}$: Training signal set (average of SSVEP)
  - $Y$: Reference sinusoidal signal set

- 3 CCA calculations & 4 correlations → huge computational complexity

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TARGET IDENTIFICATION COMPARISON

• Performance evaluation in terms of accuracy, processing time, and ITR (information transfer rate)

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<th>Complexity</th>
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<td>High</td>
<td>High</td>
</tr>
<tr>
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<td>Medium</td>
<td>Medium</td>
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<tr>
<td>PSDA</td>
<td>Low</td>
<td>Low</td>
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• Comb-CCA was chosen for the baseline algorithm in this research

\[
ITR = \left( \log_2 N_f + P \log_2 P + (1 - P) \log_2 \left( \frac{1 - P}{N_f - 1} \right) \right) \times \left( \frac{60}{T} \right)
\]

- \( P \): classification accuracy
- \( T \): average time for selection
- \( N_f \): number of targets

Performance comparison of target identification algorithms (a) Accuracy, (b) Processing time (in PC), (c) ITR (Information Transfer Rate)
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Performance comparison of target identification algorithms
(a) Accuracy, (b) Processing time (in PC), (c) ITR (Information Transfer Rate)
Proposed Algorithm: CCA-Lite

• Optimization method #1: Signal Binarization
  - Comb-CCA with multi-bit EEG & reference signal → High computational complexity / memory
  - Comb-CCA with signal binarization → Low computational complexity w/ negligible accuracy loss
    Low memory requirement

Proposed signal binarization concept for (a) EEG signal, (b) Reference sinusoidal signal
PROPOSED ALGORITHM: CCA-LITE

• Optimization method #2: On-the-fly Covariance

**Proposed Algorithm: CCA-Lite**

- **Optimization method #2: On-the-fly Covariance**
  - If \( E[XY] \gg E[X]E[Y] \) then \( E[X]E[Y] \) can be ignored
    - In our application, \( E[XY] \) more bigger than \( E[X]E[Y] \)

![Comparison of E[XY] and E[X]E[Y]](image)
PROPOSED ALGORITHM: CCA-LITE

Optimization method #2: On-the-fly Covariance


- If \( E[X Y] \gg E[X]E[Y] \) then \( E[X]E[Y] \) can be ignored
  - In our application, \( E[X Y] \) more bigger than \( E[X]E[Y] \)

- Covariance matrix calculation can be performed simultaneously with SSVEP recording

Advantage from On-the-fly Covariance Calculation
EXPERIMENTAL ENVIRONMENTS

• Low-power MCU platform
  • STM32F103ZET6 ARM MCU
    • ARM Cortex-M3 (Operating Frequency : 72MHz)
    • 512KB flash memory, 64KB SRAM

• Dataset Description *
  • EEG acquisition using Biosemi’s ActiveTwo
  • ADC : 24-bit resolution
  • Sampling Frequency : 256Hz
  • Number of channel : 8 channels (We used Oz)
  • Recording Time : 4s
  • # of Target, # of subjects : 12 targets, 10 subjects

EXPERIMENTAL RESULTS

- Subject #4
- Target: 9.25Hz

- Power spectrum of training signal according to the SSVEP recording length

![Power spectrum diagrams showing frequency differences and SSVEP recordings for various lengths.](image-url)
EXPERIMENTAL RESULTS

• Power spectrum of training signal according to the SSVEP recording length

- Subject #4
- Target: 9.25Hz
EXPERIMENTAL RESULTS

• Accuracy performance according to the combination of binarization application

**Signal binarization applied Comb-CCA**

- **Type3**: High accuracy with small memory requirement
  - Training & Reference: pre-stored data

<table>
<thead>
<tr>
<th>Type</th>
<th>Measured EEG</th>
<th>Training EEG</th>
<th>Reference Sinusoidal</th>
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<tbody>
<tr>
<td>Conv.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Type1</td>
<td>X</td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>Type2</td>
<td>X</td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td>Type3</td>
<td>X</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Type4</td>
<td>O</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Type5</td>
<td>O</td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>Type6</td>
<td>O</td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td>Type7</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

O: Signal binarization was applied
X: Signal binarization was not applied
EXPERIMENTAL RESULTS

• Accuracy performance for various target identification algorithms
  • CCA-Lite: Comb-CCA + Signal Binarization (for Train & Ref.) + on-the-fly Covariance

Accuracy at 1.5s

- CCA-Lite: 85.39%
- Comb-CCA: 86.06%
- Standard-CCA: 58.67%
- PSDA: 48.39%

Negligible Accuracy Loss
EXPERIMENTAL RESULTS

• Performance of target selection time & ITR (Information Transfer Rate)
  • Tested on Cortex-M3 based STM board (operating frequency: 72MHz)

![Graph showing performance comparison]

- 23% improved
- 93% reduced
EXPERIMENTAL RESULTS

• CCA-Lite software performance evaluation on Cortex-M3
  • M1: Signal binarization applied Comb-CCA / M2: on-the-fly covariance applied Comb-CCA
  • M1+M2: proposed CCA-Lite

Memory footprint

![Diagram showing memory footprint comparison between Conventional M2 M1 M1+M2](image)

- 92% reduced
- 47% reduced

Pure signal processing time on Cortex-M3 for single target identification

![Diagram showing pure signal processing time comparison between Conventional M2 M1 M1+M2](image)
EXPERIMENTAL RESULTS

• Overall BCI speller system performance in terms of communication speed

- Fixed target gazing time: 1.5s
- Minimum gaze shift time: 0.5s \(^1\,^2\)
- Single target identification time
  - 22% reduced!
  - Guaranteed gaze shift time 0.5s (signal processing will be done before the end of gaze shift time)

2) M. Nakanishi et al, “Enhancing Detection of SSVEPs for a High-Speed Brain Speller Using Task-Related Component Analysis”, IEEE TBME, 2018
**Reusable Matrix Arithmetic Architecture**

- SSVEP-based Target Identification SoC with Highly Reusable 8x8 QRD

**CCA: Canonical Correlation Analysis**

- CCA finds the weights $W_x$, $W_y$ which gives the largest correlation between $X$ and $Y$ (target frequency identification)
- We use CCA-Lite consisting of three CCAs.
  - Requires QRD, Inverse, Covariance, Mult.

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Xiaogang Chen, PNAS, 2015

Xiaorong Gao, 2011
**REUSABLE MATRIX ARITHMETIC ARCHITECTURE**

- SSVEP-based Target Identification SoC with Highly Reusable 8x8 QRD
  - Systolic architecture based QR decomposition engine
  - Same hardware, different operations \(\rightarrow\) high reusability (covariance, mult, QRD, inversion, …)
  - “High throughput, reduced area & memory access, reduced power consumption” compared to same operations
  - Target frequency identification on the low-cost edge devices.
  - System implementation w/ AFE & Wireless Comm.

- **System Implementation**
  - TI ADS1292 ADC Chip
  - Cortex-M3 DesignStart
  - Optional single chip
CONCLUSION

- Research for patients with paralysis
  - Low-cost wearable BCI system

- Propose CCA-Lite for low-complexity target identification
  - Target selection time reduction: 93%
  - ITR (Information Transfer Rate) improvement: 23%
  - Total performance improvement (for single target identification time): 22%

- Further work - support multi-ch EEG processing for better accuracy
  - SoC (System-on-chip) design with AFE (Analog Frontend) + dedicated hardware accelerator
THANK YOU

Any questions or comments - jihoonkim@ewha.ac.kr