EMG – Based Word Detection Sensor
BioE 101 Final Project Write Up

Roy Yao

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1 Sensor Description

1(a) Operating Principle

The sensor identifies spoken words by measuring the facial muscle electrical signals around the mouth. The device records surface EMG from the *orbicularis oris* and *mentalis* muscles with Ag/AgCl wet electrodes. A two stage band pass front end (20 Hz to 500 Hz, overall gain $\approx$ 4000) conditions the microvolt scale biopotential; the conditioned signal is digitised at 2 kHz by an Arduino MKR Zero ADC and classified into words via an autocorrelation based algorithm augmented with cosine similarity, mean squared error (MSE), and a convolutional neural network (CNN). The accuracy of word detection is about 50 – 60 %.

The main causes of the modest accuracy appear to be: (i) an inadequate SNR arising from facial EMG amplitudes of only 30 µV [Greve2021]; (ii) triangular wave distortion introduced by the band pass filter; (iii) aliasing due to the low order passive filters; and (iv) a small training set ($n = 60$) for CNN.

1(b) Theoretical Transfer Function (No Amplification)

For the first order high pass ($R_{\mathrm{HP}} = 100\,\mathrm{k\Omega}$, $C_{\mathrm{HP}} = 80\,\mathrm{nF}$) cascaded with a first order low pass ($R_{\mathrm{LP}} = 33\,\Omega$, $C_{\mathrm{LP}} = 10\,\mathrm{\mu F}$),

$$H(j\omega) = H_{\mathrm{HP}}(j\omega)\, H_{\mathrm{LP}}(j\omega) \tag{1}$$

$$= \frac{j\omega R_{\mathrm{HP}} C_{\mathrm{HP}}}{1 + j\omega R_{\mathrm{HP}} C_{\mathrm{HP}}} \cdot \frac{1}{1 + j\omega R_{\mathrm{LP}} C_{\mathrm{LP}}}, \tag{2}$$

$$\omega_{\mathrm{c,HP}} = \frac{1}{R_{\mathrm{HP}} C_{\mathrm{HP}}} \approx 125\,\mathrm{rad\,s^{-1}}\ (f_{\mathrm{c,HP}} \approx 20\,\mathrm{Hz}), \tag{3}$$

$$\omega_{\mathrm{c,LP}} = \frac{1}{R_{\mathrm{LP}} C_{\mathrm{LP}}} \approx 1900\,\mathrm{rad\,s^{-1}}\ (f_{\mathrm{c,LP}} \approx 480\,\mathrm{Hz}). \tag{4}$$

1(c) Measured Performance

The breadboard prototype exhibits a mid band gain of

$$63.53 \times 63.53 = 4036 \text{ (0.9 \% error relative to the ideal gain of 4000)}$$

and magnitude $|H(j\omega)|$ -3 dB points at 21 Hz and 495 Hz, in good agreement with theory. The large amplification compensates for the small facial EMG amplitudes, which are around 30 µV [Greve2021].

2 Design Choices

2(a) **Active devices**: Two AD620 instrumentation amplifiers were chosen for their $> 90\,\text{dB}$ CMRR, which suppresses 60 Hz power line interference and amplify the small facial EMG signals into the microcontroller's detectable range. We selected the AD620 over the LM324 because of its compact footprint, which suited our limited breadboard space. The first stage provides a gain of 63.53 and prevents loading of the high source impedance presented by the skin electrode interface; the second stage, also at $G \approx 63.53$, further amplifies the signal while buffering the subsequent RC stages.

2(b) **Passive values**: The exact R_G value was unavailable, so we used the nearest standard value,

$$R_G = 790\,\Omega \text{ (instead of } 793\,\Omega\text{)},$$

keeping the gain error below 1 %. For the filters we chose

$$R_{\text{HP}} = 100\,\text{k}\Omega,\ C_{\text{HP}} = 80\,\text{nF} \ \Rightarrow\ R_{\text{HP}}C_{\text{HP}} \approx \tfrac{1}{40\pi},$$

$$R_{\text{LP}} = 33\,\Omega,\ C_{\text{LP}} = 10\,\mu\text{F} \ \Rightarrow\ R_{\text{LP}}C_{\text{LP}} \approx \tfrac{1}{1000\pi}.$$

Our original target ($3.2\,\text{k}\Omega/0.1\,\mu\text{F}$) components were unavailable in the lab, so we substituted the closest values.

- **Filter topology**: The 20 Hz/500 Hz cut off pair spans the 20 Hz – 450 Hz facial EMG band. The design attenuates motion artefact (<50 Hz) and high frequency noise (>500 Hz), preventing these disturbances from aliasing into the signal band [DeLuca2008, McManus2020]. We selected 20 Hz as a conservative lower cut off. During testing, we observed that the bandwidth might be wider than necessary, as the signal peaks near and above 200 Hz.

First order high pass and low pass filters are isolated by an instrumentation amplifier acting as a buffer. Placing the HPF first rejects large, slow transients before amplification (as recommended in Lab 5). We later realised that a higher order filter would better suppress out of band amplification induced by the large gain.

2(c) **Gain budgeting**: The total gain of 4036 amplifies facial muscle signals of about 30 µV [Greve2021]. We used two identical stages to avoid single stage saturation and to preserve the AD620 bandwidth. In retrospect, this was unnecessary because the AD620 bandwidth at $G \approx 4000$ already covers our required band. A single \$5 INA821 at $G = 2000$ followed by a \$0.50 op amp (gain 2) would have halved the cost.

(a) **Biopotential interface**: A bipolar electrode pair over the orbicularis oris and mentalis muscles serves as the differential input, while a reference electrode on the mastoid senses the common mode potential. The mastoid was chosen because it remains stationary during speech, providing a stable reference and high facial EMG amplitude while staying outside the region of articulator motion. The electrodes convert the electrical signal into voltages to the system. Then the Arduino MKR Zero digitizes the filtered signal.

(b) **Sensor & MCU selection**: The signal chain is wet electrodes → band pass filter (AA F) → Arduino MKR Zero ADC → Jupyter Notebook algorithm. We chose readily available 3M wet electrodes, AD620 amplifiers, and the MKR Zero (using its 12 bit ADC at 10 bit resolution over a 3.3 V range) for rapid development, despite their higher quantisation noise and lack of reusability compared with dry electrodes and higher resolution ADCs.

3 Noise & Interference

3(a) **Johnson noise**: For $R = 100\,\mathrm{k}\Omega$ (each skin–electrode contact can be modeled as a $50\,\mathrm{k}\Omega$ resistor. For a differential measurement the two contacts appear in series, giving an equivalent source impedance of

$$R_{\mathrm{eq}} = 50\,\mathrm{k}\Omega + 50\,\mathrm{k}\Omega = 100\,\mathrm{k}\Omega.$$

), $T = 298\,\mathrm{K}$, and $B = 480\,\mathrm{Hz}$,

$$v_n = \sqrt{4kTRB} \approx 0.89\,\mu\mathrm{V}_{\mathrm{RMS}}.$$

3(b) **Quantisation noise**: With a 10 bit ADC (LSB = $3.22\,\mathrm{mV}$),

$$\sigma_Q = \frac{\mathrm{LSB}}{\sqrt{12}} \approx 0.93\,\mathrm{mV}_{\mathrm{RMS}}.$$

3(c) **Total broadband noise (referenced to ADC input)**: The AD620 input noise density is $9\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$, giving

$$v_{\mathrm{amp}} \approx 0.20\,\mu\mathrm{V}_{\mathrm{RMS}}.$$

Combined input noise

$$v_{\mathrm{in}} = \sqrt{0.89^2 + 0.20^2} \approx 0.91\,\mu\mathrm{V}_{\mathrm{RMS}}.$$

After $4000 \times gain$, $v_{\mathrm{out}} \approx 3.6\,\mathrm{mV}_{\mathrm{RMS}}$, slightly above the quantisation noise floor.

Other sources & mitigation: Additional disturbances include 60 Hz electromagnetic interference (rejected by the AD620's $\geq$ 90 dB CMRR and differential electrode configuration), motion artefacts near the cut off frequency (mitigated by a higher order HPF), and broadband white noise (attenuated by the LPF).

References

[Connolly2024] S. M. Connolly,
BioE 101 Lecture Notes: Instrumentation, Filters, and Noise,
UC Berkeley, 2024.

[DeLuca2008] C. J. De Luca,
A Practicum on the Use of Surface EMG Signals in Movement Sciences,
Delsys, May 2008.

[Greve2021] T. Greve, L. Wang, S. Katzendobler, L. L. Geyer, C. Schichor, J. C. Tonn, and A. Szelényi,
Bilateral and Optimistic Warning Paradigms Improve the Predictive Power of Intraoperative Facial Motor Evoked Potentials during Vestibular Schwannoma Surgery,
Cancers (Basel), vol. 13, no. 24, art. 6196, 9 Dec. 2021. PMCID: PMC8699745.

[McManus2020] L. McManus, G. De Vito, and M. M. Lowery,
Analysis and Biophysics of Surface EMG for Physiotherapists and Kinesiologists,
Frontiers in Neurology, vol. 11, p. 576729, 2020.