CLEANEMG: COMPARING INTERPOLATION STRATEGIES FOR POWER LINE INTERFERENCE QUANTIFICATION IN SURFACE EMG SIGNALS

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ABSTRACT

Quantifying 50/60Hz power line interference in surface electromyography through spectral interpolation is investigated. The quantification method is based on interpolating the signal spectrum about its 50/60Hz components to estimate the signal, and then the power line interference. Once these constituents are differentiated, a signal-to-60Hz-Noise ratio may be estimated and used as a quantifying metric. Simulations were used to compare estimation error introduced by two interpolation methods, one using the raw spectrum, and another using a smoothed spectrum. Results indicate that the smoothed spectrum method performs moderately better, but both can yield estimation errors <10% relative to signal power.

INTRODUCTION

Power line interference is a sinusoidal noise added to a signal due to the presence of a power line source near the signal. The interference manifests itself through sharp spectral components at 50/60Hz and their harmonics in the frequency spectrum. In previous work [1], we described a spectral interpolation method for quantifying power line interference in Surface Electromyography (SEMG) signals, based on the work by Mewett et al [2]. A cleaned signal spectrum was estimated about 60Hz using points extracted from a line of best fit for the edge of the spectrum containing the 60 Hz components. Results of that work indicated that interpolation of the raw spectrum in this way yielded a reasonable estimate of the interference, but that error introduced through the interpolation process decreased the overall signal-to-noise ratio (SNR) when the method was used to remove the interference in signals with signal-to-60Hz-noise ratios (SNR_{60HZ}) above about 9dB. The purpose of this work was to compare the interpolation method with a modified method for improved performance.

This work is part of an ongoing research project called CleanEMG [1],[3], the focus of which is to provide open source, user friendly signal processing tools for researchers and clinicians for quality assessment of sEMG signals. SEMG has many potential uses as a diagnostic, rehabilitative or performance measuring tool. However, these signals are difficult to measure and interpret because of their random nature, and interpretation of corrupt signals can yield misleading results [1], [2]. Since the frequency spectrum of power line interference lies within the SEMG signal spectrum, detection and reduction of power line interference can be difficult, especially when the interference is small. Quantification and reduction of power line interference is therefore, a concern in sEMG signal analysis.

METHOD

The interpolation approaches can be broadly classified in two ways - a) raw spectral interpolation and b) smoothed spectral interpolation.

Simulations were used to evaluate the spectral interpolation methods SEMG signals were simulated by passing white Gaussian noise through a shaping filter [3], [4] as delineated by the transfer function in (1).:

$$H_{EMG}(\omega) = \frac{jK\omega_h^2\omega}{(\omega_l+\omega)(\omega_h+\omega)^2} \qquad (1)$$

In (1), ω_l and ω_h are parameters that adjust the shape of the SEMG spectrum and K is a gain factor. Values of 40Hz and 80Hz were chosen for ω_l and ω_h respectively (after multiplying by 2π radian/cycle).

A set of 100 signals was simulated with a sampling frequency fs = 1000 Hz and a signal length T = 1 second.

Power line interference was also simulated and then added to the SEMG signals. The interference was simulated according to:

$$N_{60Hz}(t)=A\cos(2\pi f0t + \varphi) \qquad (2)$$

where A is the amplitude of the interference, and f0 = 60Hz, and φ = 0, represent the frequency and phase of the noise respectively. For this study, A was set to 0.5 mV and K was modified to set the signal-to-60Hz-Noise ratio, SNR60Hz to range from 0.5 to 5 (-3dB to 7dB).

Interpolation of raw FFT spectrum

An estimate of the clean sEMG signal $\hat{s}(t)$ given the corrupt signal

$$s^{'}(t)=s(t)+ N_{60Hz}(t) \qquad (3)$$

was obtained by linearly interpolating the corrupt sEMG signal spectrum about 60Hz. The spectrum was obtained using the standard Fast Fourier Transform (FFT) algorithm for the Discrete Fourier Transform. In order to interpolate the raw FFT spectrum, a best line of fit was obtained for frequencies about 60Hz. Since the model parameters used in the simulation set the 60Hz component within the falling edge of the spectrum, this edge was used to define the range in which the best line was estimated. Model parameters were used to estimate the start and end of this edge as 50Hz and 90 Hz Respectively.

Using the slope and intercept from the line, frequency values were estimated for a band of frequencies around 60Hz. This band was called the estimation frequency band in represented the region in which linear interpolation takes place. Six band widths were investigated ranging from 60Hz +/- 1Hz to 60Hz +/- 6Hz. Figure 1 illustrates the best line of fit and estimation frequency band used in the spectral interpolation process.

Interpolation was done on both magnitude and phase components of the spectrum. The estimates were substituted into the raw spectrum to produce an estimate of the clean SEMG. Spectral subtraction of the cleaned SEMG from the corrupt SEMG yielded an estimate of power line interference. Given the estimate of this 60Hz component, $\hat{N}_{60Hz}(t)$, and the actual noise $N_{60Hz}(t)$, the estimation error was defined as

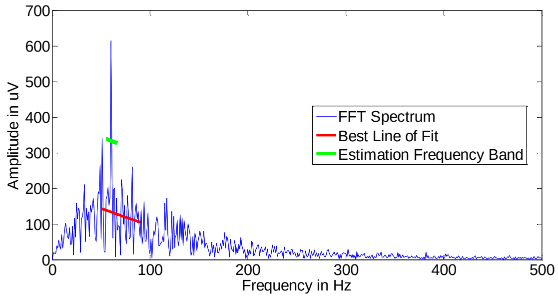

Figure 1: Spectral interpolation using a best line of fit and an estimation frequency band. The estimation band is represented by the smaller line. The peak around 60Hz in the spectrum represents power line interference.

$$E(t) = \hat{N}_{60Hz}(t) - N_{60Hz}(t) \qquad (4)$$

Power in the error signal P_{Erms} was calculated using the root mean square and normalized to the power in the clean signal, calculated in the same way. This estimation error was interpreted as both an error in estimation of the noise, and a distortion error of the SEMG, as these are equivalent.

Interpolation of smoothed FFT spectrum

An alternative to interpolating the raw spectrum was also investigated. In this method, the raw FFT spectrum was smoothed using a median average filter. In the median averaging process, some frequency points are lost due to reduced resolution through smoothing. 'Missing' frequency points lying between the 'known' frequency points in the smoothed FFT spectrum were estimated using linear interpolation. Then, spectral values for frequencies lying within the estimation frequency band were extracted and used to replace spectral values within the estimation band of the raw spectrum. Bands were defined as they were for the interpolation of the raw spectrum method. Both magnitude and phase were interpolated. The spectral values replaced the raw spectral values in the FFT spectrum to produce a cleaned sEMG signal. Estimates of power line interference and estimation error were obtained in the same way as the interpolation of the raw spectrum.

RESULTS

Power in error signals were calculated over a range of SNR's and for different estimation frequency bands. Figure 2 shows P_{Erms} values averaged across the 100 simulated signals for an estimation band value R of 2 Hz (60±2Hz). For any particular value of R, the error does not change with SNR's. This implies that power in the estimation error is independent of power in the interference.

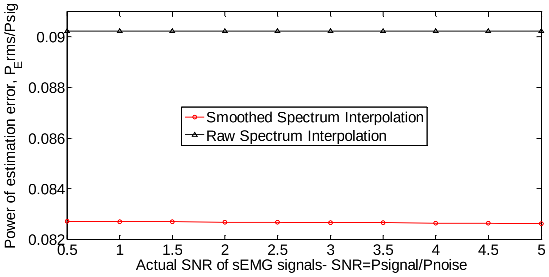

Figure 2: Estimation error powers averaged across the 100 simulated signals for the two interpolation methods for different SNRs (R=2).

Estimation error powers were calculated for a range of estimation frequency band values for SNR value set to 2. Figure 3 shows estimation error values against estimation frequency band values for the two methods. The two methods produce estimation errors that are fairly close to each other. They operated on par although when the estimation band is larger, the smoothed spectrum interpolation method yielded slightly better results than the raw spectrum interpolation method.

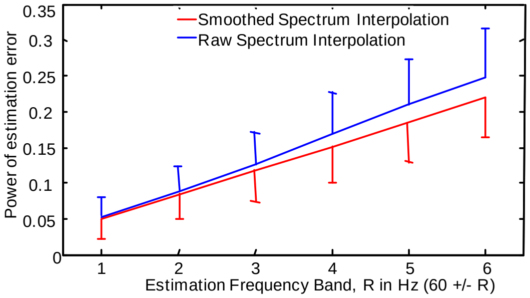

Figure 3: Estimation error powers averaged across 100 simulated signals for the two interpolation methods for different estimation band ranges (SNR = 2).

DISCUSSIONS

Two different approaches to quantifying and estimating power line interference in SEMG signals were explored. Spectral interpolation was done on the raw FFT spectrum and smoothed FFT spectrum and their performances were compared. Figure 2 indicates that the smoothed spectrum interpolation has a smaller estimation error when compared to raw spectrum interpolation, though the difference is small (<.01mV^2). Figure 3 indicates that the two approaches yielded similar performance, though for cases in which the estimation band was larger, the smoothed spectrum interpolation performed slightly better than the raw spectrum method.

The improved performance for larger estimation bands can be explained by recognizing that the nonlinear nature of the SEMG spectrum has more influence on larger estimation bands and the smoothed spectral interpolation method does a better job at estimating these nonlinearities. This may be important in mitigating against jitter in the interference about 60Hz. Jitter is defined as the variation in power line frequency. In their study on spectral interpolation, D.T. Mewett et al [2] suggested that the frequency of power line interference varies by 1 Hz (can range from 59Hz to 61Hz). Bai et al [5] have used a frequency range of 60±2Hz to account for variations in the power line frequency. The length of estimation frequency band should be consistent with the amount of jitter expected in the interference.

The shaping filter used in simulating the SEMG produced SEMG signals with a well defined spectral shape. Thus identification of rising or falling edges of the spectrum in which the interference was present was straightforward. However, the simulated signals and their spectrums may not always be a good representation of real sEMG signals and their spectrums. Therefore, defining rising and falling edges for real sEMG signal spectrums may be more difficult. This could be reduced performance of the raw spectrum interpolation method.

The powers reported here represent the power of estimation error relative to signal power. Thus, error can range from about 5% of the power in the signal to 25%, depending on the estimation frequency band range. However, even for the highest band range investigated here, the power in the estimation error remains less than power in the noise (for R = 6, raw P_{ERMS}/P_{N60Hz} = 49% for the raw spectral method). Thus, both interpolation methods have capacity to quantify and reduce power line interference.

CONCLUSION

Interpolation using a raw spectrum, and using a smoothed spectrum both show promising results for quantifying and reducing power line interference. However, interpolation using the smoothed spectrum method does not require knowledge of the rising and falling edges of the spectrum and may also be more effective than interpolation using the raw spectrum in mitigating against jitter.

ACKNOWLEDGEMENTS

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