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Phase-Locked Loop Based Cancellation of ECG Power Line Interference

LI Taihao[1,2], ZHOU Jianshe[1], LIU Shupeng[3], SHI Jinsheng[1], and REN Fuji[4]

(1. Beijing Advanced Innovation Center for Imaging Technology, Capital Normal University, Beijing 100048, China;
2. Flatley Discovery Lab, Boston 02129, USA;
3. School of Communication and Information Engineering, Shanghai University, Shanghai 200072, China;
4. Department of Information Science and Intelligent Systems, University of Tokushima, Tokushima 7708506, Japan)

Abstract

Power line (PL) interference is one significant artifact in electrocardiography (ECG) that needs to be reduced to ensure accurate recording of cardiac signals. Because PL interference is non-stationary and has varying frequency, phase, and amplitude in ECG measurement, adaptive techniques are often necessary to track and cancel the interference. In this paper we present a phase-locked loop (PLL)-based adaptive filter to cancel PL interference. The PLL obtains the reference signal that is fed into the adaptive filter to remove the PL interference at the central frequency of 50 Hz. It is found that the technique can effectively cancel PL interference in real ECG signals and, when compared with some existing techniques such as least mean squares (LMS) adaptive filter, the new technique produces better results in terms of signal-to-interference ratio (SIR).

Keywords

phase-locked loop; ECG; adaptive filter; power line cancellation

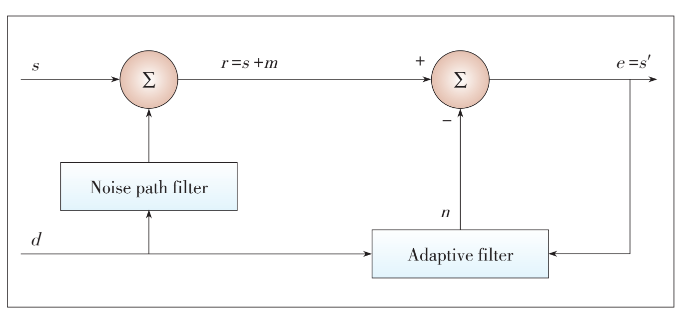
1 Introduction

Electrocardiography (ECG) is extensively used for detecting heart disease by recording the electrical activity generated by cardiac muscles. In ECG measurement, the cable linking the subjects to the ECG monitor is susceptible to the 50 Hz power line (PL) interference [1], which results in inaccurate reading because the interference frequency is located very close to the high frequency component of the true ECG signal [2]. Studies showed that, to achieve high quality for ECG, the amplitude of the PL interference must be kept at less than 0.5% of the peak-to-peak amplitude of the QRS waves [3]. Therefore, removing or cancelling the PL interference is a critical challenge in ECG signal processing. In the last several decades many methods have been proposed to cancel the PL interference and they can be generally categorized into non-adaptive and adaptive filtering. Non-adaptive filters such as notch filter have the advantage of featuring a simple structure and fixed coefficients, however, they cannot target PL interference when its frequency deviates from 50 Hz [4]–[6]. From this perspective, adaptive filtering, because of its ability to track the frequency of PL interference, may yield more robust performance in practice [7]–[11]. In implementation, adaptive filtering relies on the stochastic characteristics of a reference signal to track the PL interference. In this work, we propose a method to first use phase-locked loop (PLL) to generate the reference signal that can be used to track the frequency and phase of PL interference accurately. We then use a least mean squares (LMS) filter to cancel the PL interference from ECG signal for a better result. We use the ECG data from the MIT-BIH database to test our method and found that it performed superior to the existing techniques.

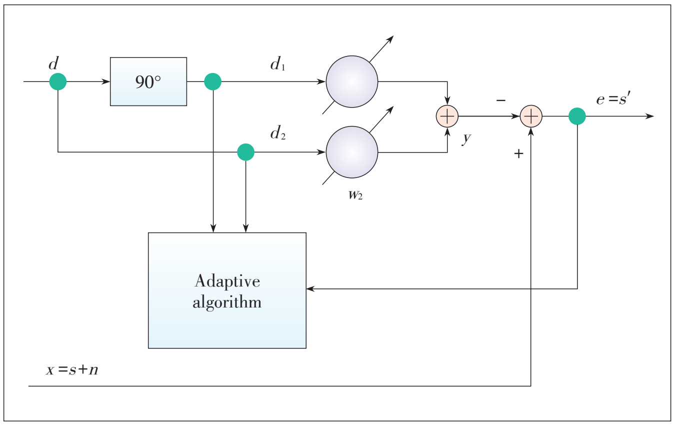
2 Methodology

The model of our ECG signal and the structure of the adaptive filter is shown in **Fig. 1**, where s is the original uncontaminated ECG signal. The PL interference at 50 Hz is represented by d. However, as the PL interference will deviate from 50 Hz in frequency and phase in practice, we model this process as a noise path filter f such that $u=f(d)$. Hence, our received signal is $r=s+u$. The adaptive filter g takes d as one of its inputs to mimic the process of f to generate an output v such that the difference between u and v is minimized, and therefore the final output e is the best estimator of s in terms of mean square error (MSE).

In our work, the adaptive filter in Fig. 1 has the form of PLL. Its detailed structure is shown in **Fig. 2**, where d_1 and d_2 are the 50 Hz reference sine waves that have a phase difference of 90°. The coefficient vector is composed of w_1 and w_2, which are updated by the adaptive filter. The adaptively estimated 50 Hz reference signal is y. Given a noisy observation r, we can



▲**Figure 1. Principle of adaptive noise cancellation.**



▲**Figure 2. The cancellation scheme of 50 Hz power line interference.**

obtain an estimation $\hat{s}$ of the true signal in the form of a LMS filter as below:

$$w_1(n+1) = w_1(n) + \mu e(n) d_1(n), \tag{1}$$

$$w_2(n+1) = w_2(n) + \mu e(n) d_2(n), \tag{2}$$

$$v(n) = w_1(n) d_1(n) + w_2(n) d_2(n), \tag{3}$$

$$\hat{s}(n) = r(n) - v(n), \tag{4}$$

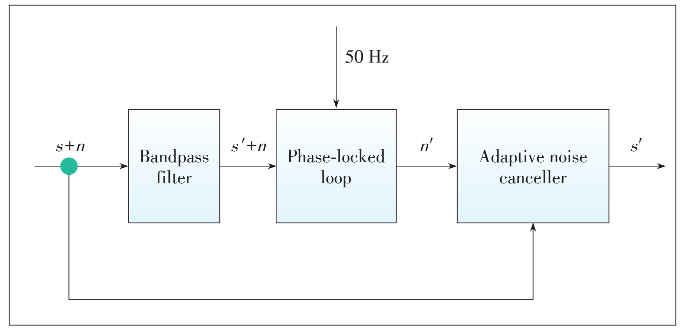
where μ is the step size of LMS process.

3 Proposed Method

It has been shown by Widrow and Glover [10] that once the parameter estimates have converged and are fixed, an adaptive power line interference (PLI) canceller is approximately equivalent to a notch filter. However, in practice the PL frequency is not stable or not accurately known a priori, and a mismatch between the reference signal frequency and the PLI frequency might lead to inadequate reduction of the PLI. In this paper we propose a new method to solve the problem and take the concept of PLL in communication theory. The PLL tracks the PLI frequency and outputs a reference signal whose frequency is perfectly equivalent to that of the PLI [11].

The proposed model is shown in **Fig. 3**.

In Fig. 3, the noisy ECG signal $s+n$ is filtered by a bandpass filter centered to 50 Hz in order to suppress signals outside PLI band, the filter output contains PLI and noise. According to PLL theory, once the input signal frequency is in the PLL hold in range, the PLL can acquire the frequency of input signal and keep an output signal synchronizing with the input signal in frequency as well as in phase [12]. The natural frequency of PLL is 50 Hz, and the PLL will track the PLI in frequency and phase. When the acquisition succeeds, the misadjustment between the parameter estimates and the actual parameters is small enough and the PLL gives a perfect reference signal whose frequency is always the same as PLI within the PLL track range.



▲**Figure 3. The proposed model.**

The most popularly used PLL in practice is second-order, and its closed-loop transfer function may be written as follows.

$$H(s) = \frac{2\xi\omega_n s + \omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}, \tag{5}$$

where ω_n is the natural frequency and ξ is the loop damping ratio. The ξ usually takes the value 0.7. According the PLL theory, the lock-in range of a second-order PLL is

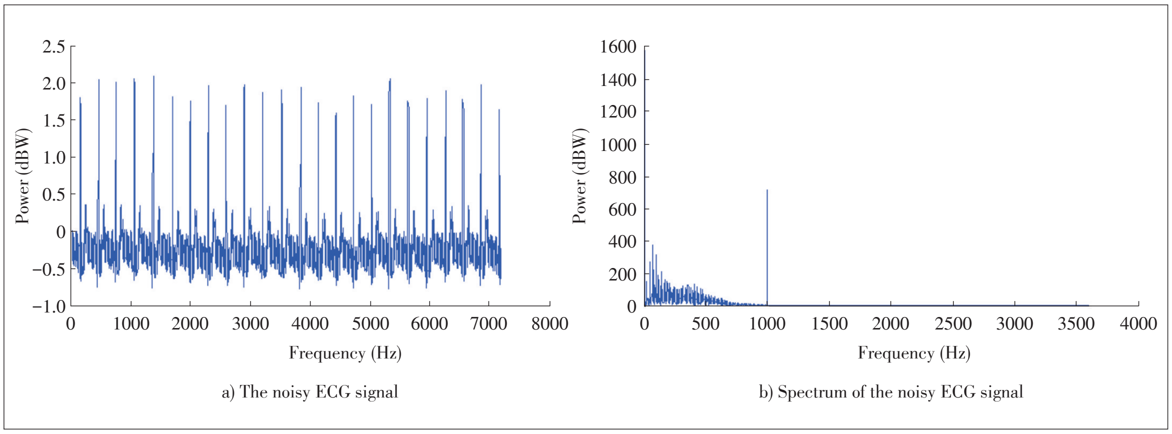
$$\Delta\omega = 2\xi\omega_n. \tag{6}$$

The PLL can acquire the input signal immediately as long as the input signal frequency is in the lock-in range of PLL.

4 Experimental Results and Analysis

We used the MIT-BIH ECG data to test our method and compared it with an existing technique. The database consists of 48 half-hour excerpts of two channel ambulatory ECG recordings that are digitized at 360 samples per second per channel. The data have an 11-bit resolution over a 10 mV range and they have been amplified with gain of 200 [13].

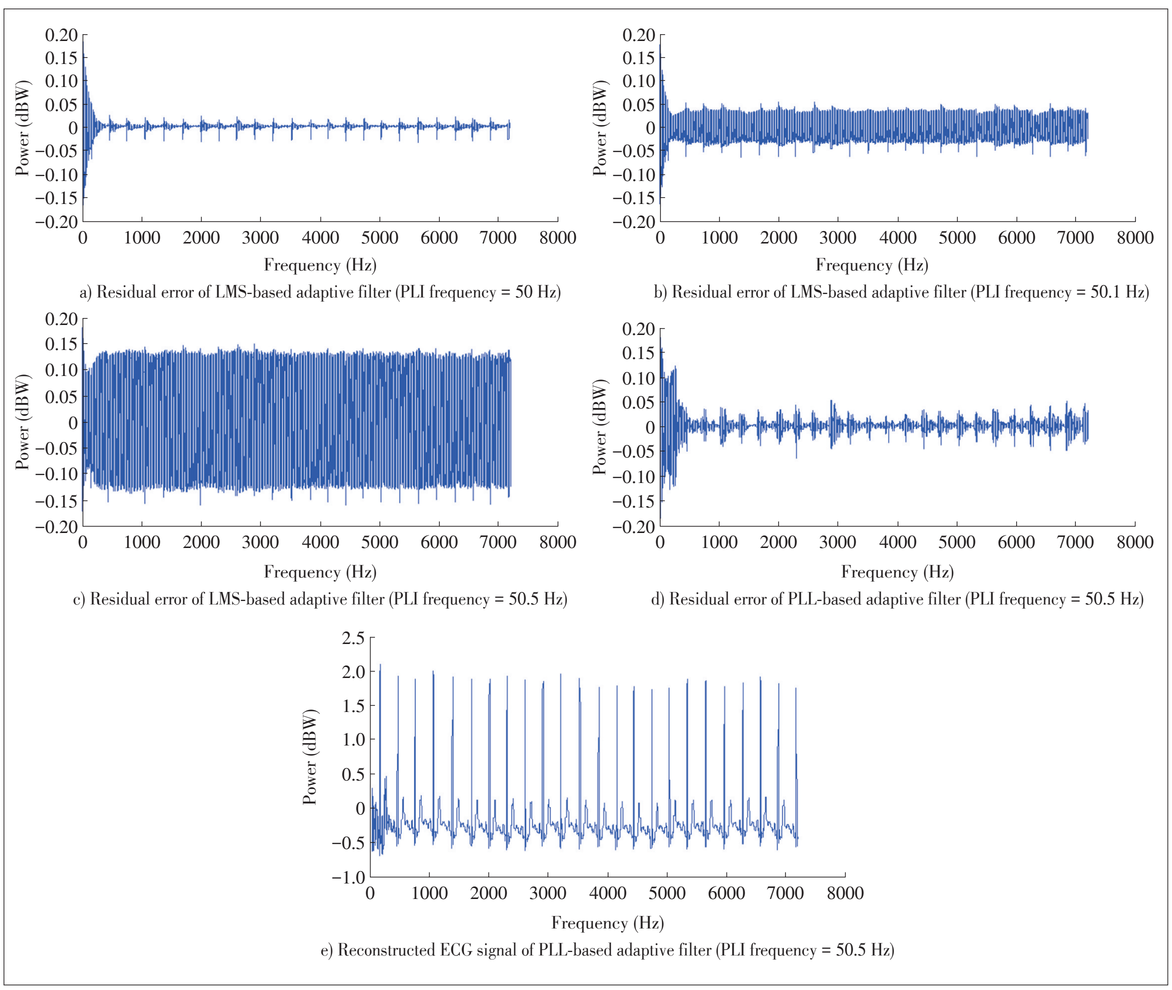
Fig. 4 shows a noisy ECG signal (the sum of record 103 and 50 Hz PL interference, Signal Noise Ratio= 0 dB) and its spectrum. The recording began at 50 second after the ECG started. The waveform of the ECG was completed submerged under the PL interference (Fig. 4a). The spectrum of the PL interference can be clearly observed in Fig. 4b. **Fig. 5** compares the performance of LMS filter and our proposed method in cancelling PL interference at different frequency deviations. Fig. 5a shows the MSE of an LMS filter to cancel PL interference at 50 Hz. Because there was no frequency deviation, the LMS filter was able to achieve satisfactory performance. When the frequency of PL interference deviated to 50.1 Hz, the performance of the LMS filter decreased as it generated more errors (Fig. 5b). When the frequency of PL interference was further deviated to 50.5 Hz, the LMS filter created much larger MSE (Fig. 5c). For the same scenario, our method was able to achieve very good performance to maintain a small MSE (Fig. 5d). The reconstructed ECG signal of our method in this case



a) The noisy ECG signal

b) Spectrum of the noisy ECG signal

◀**Figure 4.**
The noisy ECG signal.



a) Residual error of LMS-based adaptive filter (PLI frequency = 50 Hz)

b) Residual error of LMS-based adaptive filter (PLI frequency = 50.1 Hz)

c) Residual error of LMS-based adaptive filter (PLI frequency = 50.5 Hz)

d) Residual error of PLL-based adaptive filter (PLI frequency = 50.5 Hz)

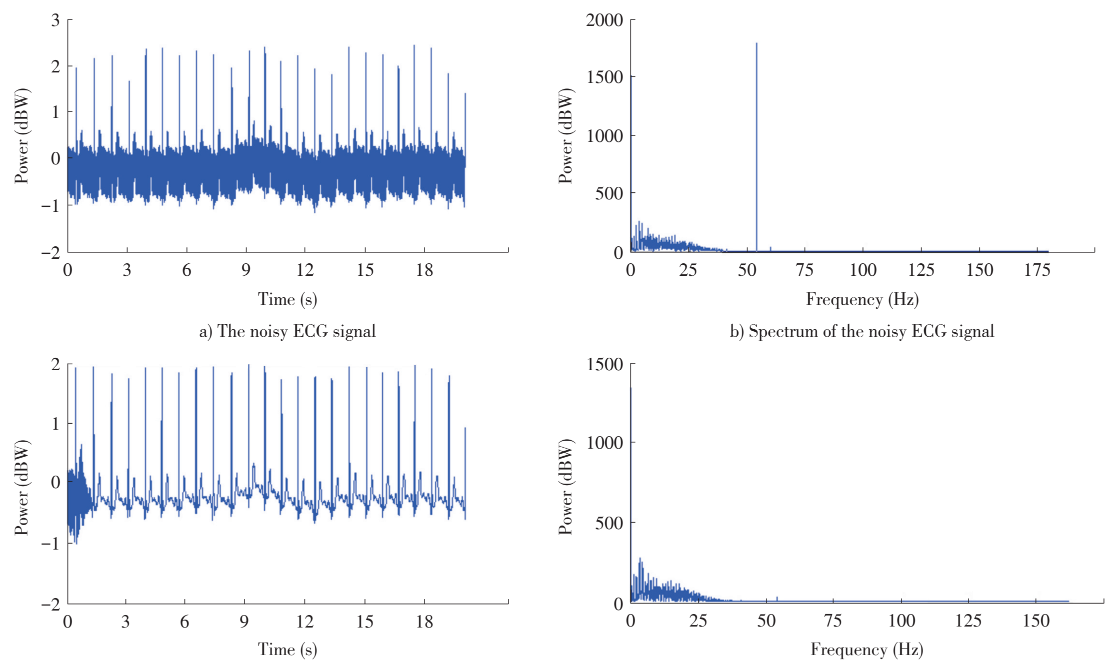
e) Reconstructed ECG signal of PLL-based adaptive filter (PLI frequency = 50.5 Hz)

◀**Figure 5.**
The proposed method.

was plotted in Fig. 5e), from which we can easily observe the true ECG components. **Fig. 6** shows that the proposed PLL-based canceller can track and lock the frequency deviation in about 1 second and suppress the PL interference completely.

For quantitative comparison, we simulated different *SIRs* as the input to the noise cancellation techniques where SIR_{in} is defined as the ratio between the power of true ECG signal s and the amplitude of the PL interference. We then calculated the SIR_{out} at the output of the LMS filter and our method. For an accurate quantification of the cancellation performance, the SIR at the input and output of the canceller must be known. **Table 1** compares the performance of the two methods for a fixed PL interference frequency at different SIR_{in}。

Table 2 compares the two methods at a fixed SIR_{in} but for different degrees of frequency deviations of the PL interference. It can be seen that the PLL-based canceller is robust to



a) The noisy ECG signal

b) Spectrum of the noisy ECG signal

c) PLL-based ECG signal

d) Spectrum of the PLL-based ECG signal

◀**Figure 6. Tracking performance (Δf/f=8%).**

▼**Table 1. Performance comparison at different SIR_{in}**

SIR_{in} (dB)	N	−20	0	20
SIR_{out} (dB)	AF	35.02	35.02	35.02
	PLL-based AF	25.87	29.47	30.07

AF: Adaptive Filter PLL: Phase-Locked Loop SIR: Signal-Interference Ratio

▼**Table 2. Performance comparison at different frequencies (SIR_{in} = 0 dB)**

Fixed SIR_{in} (dB)	SIR_{out} (dB)		
Δf/f	0.1%	1%	10%
AF	20.11	2.7	−0.92
PLL-based AF	28.16	28.59	31.42

AF: Adaptive Filter PLL: Phase-Locked Loop SIR: Signal-Interference Ratio

frequency deviation, and the SIR_{out} is about 30 dB regardless of frequency deviation.

5 Conclusions

This paper proposes a PLL-based adaptive canceller for the suppression of the PL interference in ECG recordings. The canceller comprises a second-order PLL, so except amplitude and phase, the frequency deviation can be tracked. Our experiment results showed that the proposed canceller could track PL interference even when its frequency deviated 10% from 50 Hz and lock the tracking in one second. Therefore, our method can obtain a high performance ECG output with the SIR of about 30 dB, and it is robust to frequency deviation. As a conclusion, the proposed method is superior to the common adaptive noise canceller. As a PL interference cancellation technique, our method is also applicable to neural recording such as electroencephalography [14] and wearable biomedical instruments [15].

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Biographies

LI Taihao (litaihao@heartdynamic.cn) received the M.S. and Ph.D. degrees in information system engineering from University of Tokushima, Japan in 2003 and 2006, respectively. During 2006–2011, he was a postdoc researcher at Harvard University, USA. He is now a professor with Beijing Advanced Innovation Center for Imaging Technology, Capital Normal University, China. His research interests include affective computing, natural language processing, and artificial intelligence.

ZHOU Jianshe (zhoujianshe@solcnu.net) is a board member of Chinese Linguistics Association, a director member of Expert Committee of the Linguistics Committee of Beijing, and the deputy director of Beijing Linguistics Association. He is the vice president of Capital Normal University, China and a professor with Beijing Advanced Innovation Center for Imaging Technology there. His research interests include linguistics, neuroscience, and algorithms.

LIU Shupeng (liusp@i.shu.edu.cn) received his Ph.D. degree in 2007 from Shanghai Jiaotong University, China. He is an associate professor with School of Communications and Information Engineering, Shanghai University, China. His research interests include signal processing, Raman spectra, and image processing.

SHI Jinsheng (shijsh@aliyun.com) received his Ph.d. degree from Nankai University, China. He is a professor at Capital Normal University, China. His research interests include linguistics, affective computing.

REN Fuji (ren@is.tokushima-u.ac.jp) received his B.E. and M.E. degrees from Beijing University of Posts and Telecommunications, China in 1982 and 1985, respectively. He received his Ph.D. degree in 1991 from Hokkaido University, Japan. He is a professor at the Faculty of Engineering, the University of Tokushima, Japan. His research interests include natural language processing, affective computing, artificial intelligence, and language understanding.