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Filtering of Intended Motion for Real-time Tremor Compensation in Human Upper Limb using Surface Electromyography

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Abstract— **The recorded motion from (pathological) tremor patient may consist of the involuntary tremulous component and the intended motion. These two components have to be separated so that the actuation part will be able to suppress only the tremor. This paper proposes an algorithm to remove the intended motion by using an extended Kalman filter with the help of adaptive high-pass filter. The effectiveness of the algorithm is also shown in the presence of stimulation artifacts. It is part of the active pathological tremor compensation project for human upper limb.**

I. Introduction

THE recorded upper limb motion of a person with tremor may consist of the involuntary tremulous component and his intended motion. These two components have to be separated so that the tremor can be suppressed. Our proposed active tremor compensation obtain signals from human upper limb motion through accelerometer (ACC) and surface electromyography (sEMG) [1]. After the separation Functional Electrical Stimulation (FES) is used to attenuate the tremor in anti phase, i.e. if tremor is detected in the agonist, FES will counteract it by actuating the antagonist. The proposed filtering method in this paper is based on Extended Kalman Filter. Phase delay due to the low pass filter used in rectification of sEMG signal is minimized. FES artifact [2] is also considered. Finally in the last section it is shown that it is possible to attenuate tremor as it occurs by utilizing the electromechanical delay [3].

II. Preliminaries

A. Experiment setup

The hardware setup for the tremor compensation system is shown in Fig. 1. The sEMG amplifier is EMG100C from Biopac Systems, Inc., USA, set to pass 10-500 Hz with 500 times magnification. The FES system is Compex 2 from Compex SA, Switzerland. It has two analog inputs which is used to control the stimulation output, e.g. its amplitude and when to start/stop the actuation. Real-time operating system (QNX ver. 6.3.B4, QNX Software System International Corporation, Canada) is used in the PC to guarantee an iteration time as short as 0.2 ms or 5 kHz sampling rate. In this paper FES will not be included in the loop since the focus is on the filtering of intended motion.

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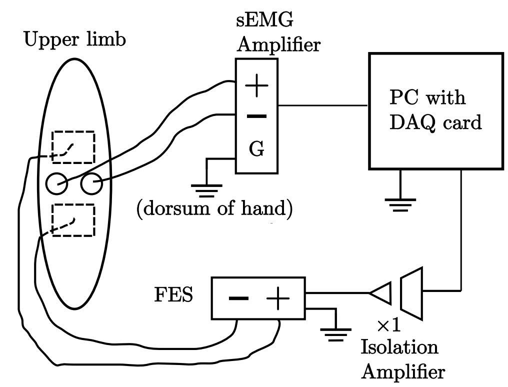

Fig. 1. Hardware setup of real-time tremor compensation.

B. Input signal

SEMG data taken from a Holmes' tremor patient is shown in Fig. 2. The data is taken during finger-to-nose test whereby the patient is asked to touch his nose and stretch to a target in front of him repeatedly. For our interest here, only the sEMG data from the wrist flexor (flexor carpi ulnaris, Fig. 2–middle) will be considered. The small but frequent burst seen in the wrist flexor is the tremor. Added into that is the intended motion (larger signal but less frequent) as shown in the top part of Fig. 2. To provide a more focused information, full rectification and a low-pass filter is applied to the raw sEMG signal (Fig. 2–bottom).

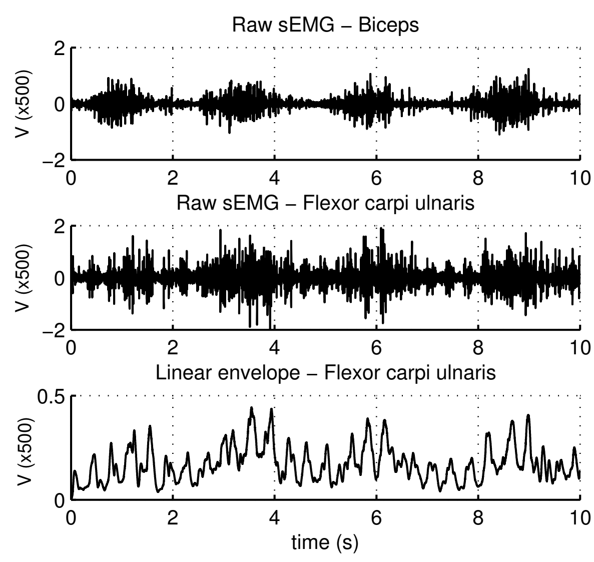

Fig. 2. SEMG signal of Holmes' tremor patient.

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III. Methods

The overall proposed algorithm to remove the intended motion is given in Fig. 3. Linear envelope of raw sEMG is obtained by full rectification and 2nd order elliptic filter with 0.5 dB peak-to-peak ripple and 40 dB minimum stop band attenuation, at 5 Hz cutoff frequency. Elliptic filter is chosen because it provides a better attenuation with less order compared to a Chebyshev or Butterworth filter. Furthermore the phase delay incurred by the elliptic filter is slightly lesser than that incurred by the other filters. Second-order filter is chosen over first-order because it has sharper transition band. Nevertheless the problem with classical low-pass filter is that it incurs phase delay which is undesirable. This issue will be considered in the following subsection.

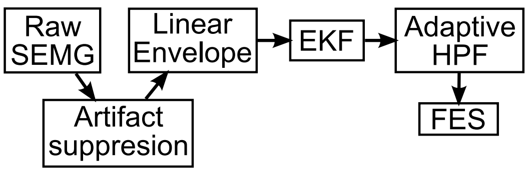

Fig. 3. Flowchart of the intended motion filtering algorithm

A. Adaptive high pass filter

If a sinusoid is passed through a known low-pass filter, the phase delay can be canceled by designing a high pass filter correctly. However if the sinusoid has time-varying parameters, the high pass filter must be changed adaptively. This is the main idea of the high-pass filter developed in [4].

The linear envelope of tremor sEMG is not a stationary signal but it is slowly varying in term of its frequency within a narrow band (2-5 Hz for pathological tremor). With the assumption regarding the input signal, the problem boils down to designing an adaptive high pass filter which cancels the phase lag caused by the low-pass filter. The design of the high pass filter is done offline through brute force method summarized below [4]:

1) *Offline*: Assuming the input signal frequency is 2, 2.5, 3, 3.5, and 4 Hz, a 2nd order elliptic high pass filter is found for each frequency such that the phase lead of the high pass filter is equal to the phase delay of the low-pass filter. This is done by checking the high pass filter of a slowly incremented cutoff frequency (thus the brute force method). The result is shown in Fig. 4.
2) *Offline*: It can be seen that the poles and zeros have linear relationships with the frequency (shown by a line as a visual aid in the figure). Thus by using linear regression, the relationship is obtained.
3) *Online*: An algorithm to find the tremor frequency is needed so that the frequency can be used to design the phase balancing high pass filter. In this paper, the EKF developed in [1] is employed and shortly described in the next subsection.
4) *Online*: Using the estimated frequency from the EKF and the relationship calculated from point 2, the high pass filter can be designed and applied to the signal.

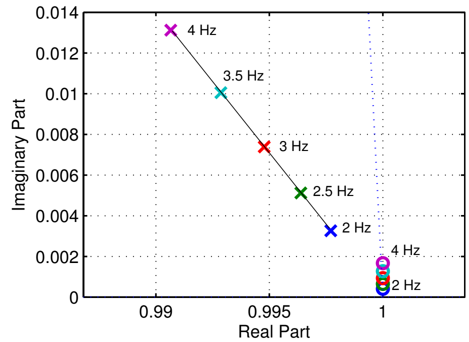

Fig. 4. Zero-pole plot of the high pass filters derived with brute force method. There are actually two roots but each is complex conjugate of the other.

B. Extended Kalman Filter (EKF)

To estimate the tremor frequency adaptively and the intended motion, a slight modification of the EKF proposed in [1] is used.

$$y(k) = r(k)\sin(\theta(k)) + b(k) \tag{1}$$

$$\theta(k) = \sum_{\kappa=1}^{k} \omega(\kappa)T + \phi(k) \tag{2}$$

where $y(k)$ is the tremor signal (linear envelope of raw sEMG), $\theta(k)$ is the total phase which consists of the varying frequency $\omega(k)$ and the relative phase $\phi(k)$. The intended motion is modeled as $b(k)$. All the varying parameters of the signal is assumed to behave as random walk. The rate of the random walk is determined by the process noise. The process model for the EKF is given below and is linear.

$$\begin{bmatrix} r(k+1) \\ \omega(k+1) \\ \theta(k+1) \\ b(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r(k) \\ \omega(k) \\ \theta(k) \\ b(k) \end{bmatrix} + \mathbf{w}(k). \tag{3}$$

With respect to implementation issue, the data is obtained with 1000 Hz sampling rate, but the measurement update is run only at 100 Hz. In between both measurement updates only time update occurs and the innovation vector is set to zero. This is to save computational time as the measurement update loop is skipped 90% of the time.

C. FES artifact suppression

After the signal is passed through the adaptive high pass filter, a simple threshold can be used to determine when to start the actuation (via FES). It means, assuming the signal only consists of tremor, anything above a certain noise level is considered as tremor; thus the other muscle will be stimulated.

However FES stimulation will affect sEMG reading [2]. Hence an artifact suppression algorithm [5] is proposed for real-time tremor compensation system. The algorithm consists of software blanking and comb filter. The blanking starts when sEMG data is sensed to be bigger/smaller than a specified threshold (bigger than the maximum sEMG level of the subject). Then for a certain period of time (4 ms, also

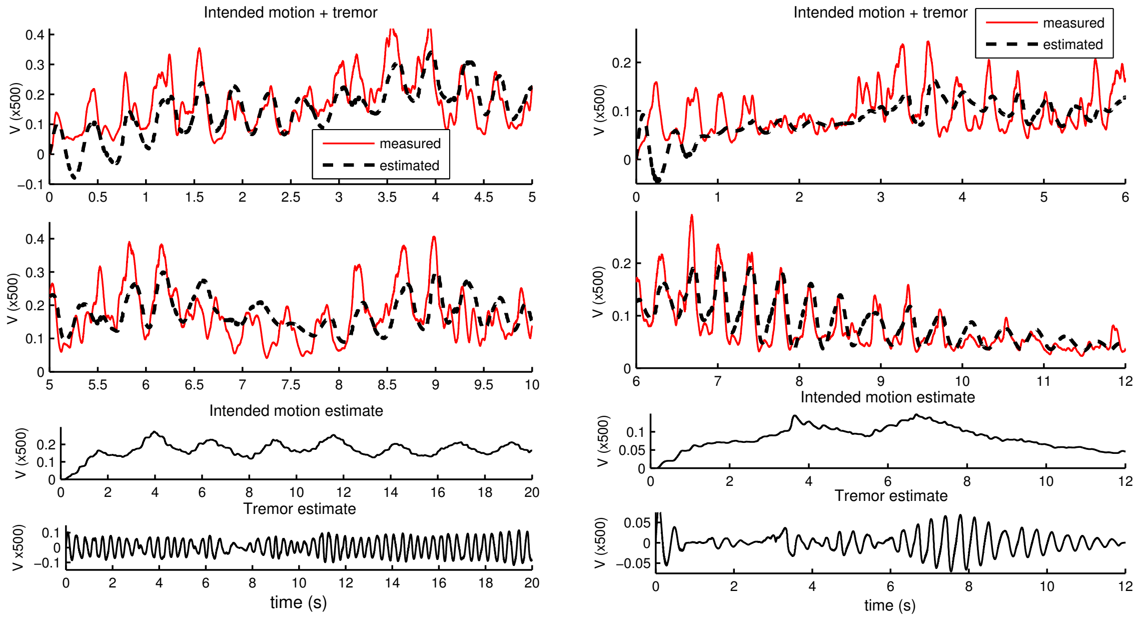

Fig. 5. Result of EKF algorithm to separate tremor from intended motion in finger to nose experiment (left) and Archimedean spiral drawing (right).

specified beforehand) the recorded sEMG data is set to be zero. The comb filter is used to reduce the residual further and 50 Hz power line interference.

IV. Results and Discussion

The FES artifact suppression algorithm described before is not able to remove the artifacts completely. Therefore the effect of the sEMG signal with the artifact residual (after processed through the suppression algorithm) on the EKF algorithm is investigated. Because no trials with FES has been done with tremor patients, the experiment is carried out on a healthy subject simulating tremulous movement. It has been found that voluntarily simulated tremor shares many similarities with pathological tremor [6]. The subject tries to simulate 2.5 Hz wrist tremor with the aid of a beeping sound with that frequency (without any intended motion). At the same time, FES is applied constantly on wrist flexor (pulse width = 200 μs, frequency = 25 Hz, amplitude = 10 mA). SEMG is recorded at wrist extensor and EKF is run to estimate the tremor parameters. It can be seen from Fig. 6 that the EKF is still able to estimate the tremor parameters.

The result of EKF in separating tremor and intended motion is shown in Fig. 5 (left). In that figure the data used is that from Fig. 2 (finger-to-nose action). Note that the dataset used has no FES interference since it is just recording of sEMG data. It can be seen that the EKF can separate the intended motion from the tremor. Another set of tremor data is tested with the algorithm. In this dataset the same patient was asked to follow an Archimedean spiral on paper with a pen. The result in Fig. 5 (right) also show a good separation between intended motion and tremor.

To see the effectiveness of the adaptive high-pass filtering algorithm, the phase lead between the output signal and the EKF input signal, which is the linear envelope of raw sEMG data, is calculated by cross correlation function. As

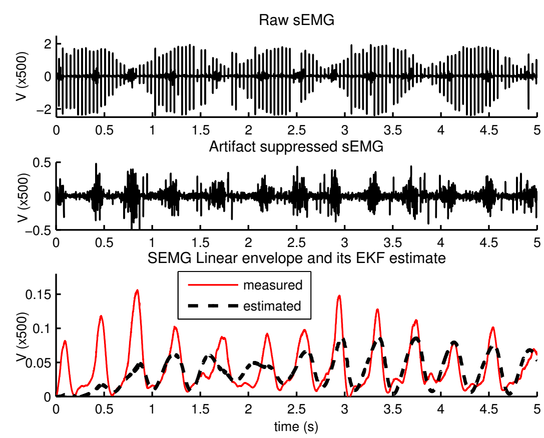

Fig. 6. Raw sEMG with FES artifacts(top); its linear envelope and the EKF estimate (bottom).

the ground truth, the raw sEMG data is filtered using the zero phase filtering routine from Matlab, instead of a standard low-pass filter. The lead between the output signal and the zero-phase filtered input signal is calculated again. Ideally the first lead should be the same as the second, although it is likely that it will be smaller. It means that the adaptive high-pass filtering cannot fully compensate the phase delay incurred by the low-pass filter.

It was thought that the frequency estimation of the adaptive filter is a reason why the adaptive high-pass filtering cannot work perfectly. Therefore the STFT is applied to the signal (Fig. 7). The frequency estimate from EKF is almost consistent with the estimate from STFT except during the 7^{th} to 8^{th} second. Here what probably happens is that the EKF is tracking the intended motion instead of the tremor, but was able to subsequently retrace the tremor.

This problem can be overcome by reducing the rate of random walk of the frequency in the EKF. Furthermore the random walk model is generalized with a first-order autoregressive model:

$$\omega(k) = \lambda\omega(k-1) + (1-\lambda)\bar{\omega} + w(k), \quad (4)$$

where $\bar{\omega}$ is a predetermined average value of ω. When $\lambda = 1$, it is reduced to the random walk model. But if λ is reduced, more weight is given to the predetermined average value, which will prevent the EKF to track other components. The effect of modifying the EKF (using $\lambda = 0.99$) is shown in Fig. 7 and the phase lead is shown in Table I. It shows that with $\lambda = 0.99$, 77% of the phase delay can be compensated, compared to 62% when $\lambda = 1$.

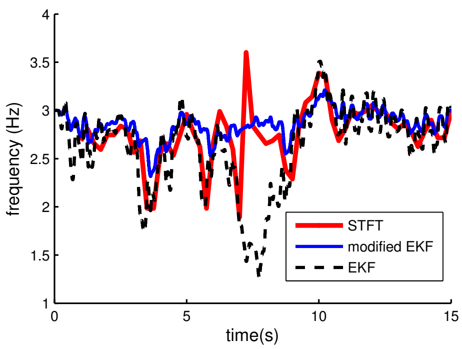

Fig. 7. Tremor frequency estimation using STFT and EKF (normal and modified).

TABLE I

EFFECTIVENESS OF ADAPTIVE HIGH-PASS FILTERING

Phase lead in samples	$\lambda = 1$	$\lambda = 0.99$
Standard low-pass	31	34
Zero-phase low-pass	50	44

V. ELECTROMECHANICAL DELAY

In our proposed real-time system for active tremor compensation (Fig. 1, electromechanical delay (EMD) is utilized for all the processing necessary to compensate tremor at that point of time. Thus phase delay should ideally be compensated so that EMD can be fully exploited.

In [7], EMD caused by voluntary motion is longer than that caused by FES. The reason suggested is the different muscle fiber recruited during voluntary and involuntary motion. In their work, the muscle tested is gastrocnemius and the FES is applied in the tibial nerve in the popliteal fossa. The method to define the onset of the motion in both neuromuscular and kinematic data is not mentioned.

Experiments to confirm the result above were carried out. FES will be applied directly to the muscle (wrist flexor, in contrast to [7]). The actual motion is recorded by goniometer (Biometrics). The subject was asked to simulate 2.5 Hz tremor at wrist flexion, with the aid of a sound cue. To determine the onset of flexion in goniometer, numerical differentiation is used because the motion data resembles sine wave. The peaks of the motion data are, therefore, the onset of the flexion/extension. Single threshold is used to determine the onset of sEMG data. For the test with FES, sEMG onset is the same as when FES starts. This can be located by looking at the FES artifacts. Offline zero phase low-pass filtering is applied when necessary to reduce noise. The EMD estimates (difference between onsets from goniometer and sEMG data) are shown in Table II.

TABLE II

EMD ESTIMATES IN MILLISECOND FROM $\pm$30-SECOND DATASETS

EMD in ms	Set 1	Set 2	Set 3
Voluntary	62.55 ± 14.35	54.48 ± 15.69	73.89 ± 10.64
Involuntary	37.05 ± 4.42	42.52 ± 5.41	35.38 ± 4.49

The result shows that it is able to cancel the tremor immediately since receiving sEMG data. The necessary processing can be done and then the output will be delayed accordingly so that FES can attenuate the tremor at the right time. This leaves us with online estimation of EMD and probably modification in the EKF. Inertial sensor such as accelerometer can be used in conjunction with EMG to get the EMG estimate. Furthermore, if there is enough computational time, the adaptive high pass filter may not be necessary, although the delay incurred by the low-pass filter should still be obtained.

VI. CONCLUSION

An EKF-based algorithm to filter off the intended motion from tremor has been proposed for real-time active tremor compensation system. To compensate the phase delay due to the inherent filtering, an adaptive high pass filter has been implemented. Issues regarding electromechanical delay have also been considered. This study further supports the feasibility of real-time active pathological tremor compensation.

REFERENCES

[1] F. Widjaja, C. Y. Shee, W. L. Au, P. Poignet, and W. T. Ang, "An Extended Kalman Filtering of accelerometer and surface electromyography data for attenuation of pathological tremor," in *IEEE RAS / EMBS International Conference on Biomedical Robotics and Biomechatronics*, Scottsdale, Arizona, 2008, pp. 193–198.

[2] K. C. McGill, K. L. Cummins, L. J. Dorfman, B. B. Berlizot, K. Luetkemeyer, D. G. Nishimura, and B. Widrow, "On the nature and elimination of stimulus artifact in nerve signals evoked and recorded using surface electrodes," *IEEE Transactions on Biomedical Engineering*, vol. 29, no. 2, pp. 129–137, 1982.

[3] D. M. Corcos, G. L. Gottlieb, M. L. Latash, G. L. Almeida, and G. C. Agarwal, "Electromechanical delay: An experimental artifact," *Journal of Electromyography and Kinesiology*, vol. 2, no. 2, pp. 59–68, 1992.

[4] W. T. Ang, M. Krichane, and T. Sim, "Zero phase filtering for active compensation of periodic physiological motion," in *IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, vol. 2006, 2006, pp. 182–187.

[5] D. Zhang and W. T. Ang, "Reciprocal EMG controlled FES for pathological tremor suppression of forearm," in *IEEE International Conference of EMBS*, Lyon, France, 2007, pp. 4810–4813.

[6] P. R. Burkhard, J. W. Langston, and J. W. Tetrud, "Voluntarily simulated tremor in normal subjects," *Neurophysiologie Clinique/Clinical Neurophysiology*, vol. 32, no. 2, pp. 119–126, 2002.

[7] J. T. Hopkins, J. B. Feland, and I. Hunter, "A comparison of voluntary and involuntary measures of electromechanical delay," *International Journal of Neuroscience*, vol. 117, no. 5, pp. 597–604, 2007.