ADAPTIVE HUMAN-MACHINE INTERFACE FOR PERSONS WITH TREMOR

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ABSTRACT

A new adaptive filter has been developed to model pathological tremor during human-machine interaction. Operating online, the system suppresses tremor to improve precision in human-machine control. Offline, the system processes recorded data to quantify tremor for clinical use. The filter estimates tremor frequency as well as amplitude, adapting the reference input frequency to follow frequency modulation of tremor. The algorithm is computationally inexpensive and simple to implement in many human-machine interface applications. Experimental results are presented.

I. INTRODUCTION

In an increasing number of situations, human-machine control is becoming essential to fully participating in society. Examples include computer mice, computer pen input (e.g., personal digital assistants (PDA's)), and dextrous teleoperation, both real and virtual [1,2]. As these become more widespread, accessibility of modern human-machine control to disabled persons is a primary aim of rehabilitation technology [2]. For these users, assistive interfaces for human-machine control enhance quality of life, personal independence, and competitiveness in the employment market.

Many persons are disabled by pathological tremor, which is approximately sinusoidal involuntary motion stemming from conditions such as essential tremor, multiple sclerosis, and brain injury [3]. It constitutes an additive noise in human control of movement [4]. Its frequency tends to be within the range 2-12 Hz [3], while voluntary motion frequency tends to be lower. Low pass filtering has been used successfully to attenuate tremor [3,4]. However, a low pass filter with cutoff frequency low enough to attenuate the entire 2-12 Hz range also places an undesirably restrictive limit on voluntary frequency content. A notch filter offers the possibility of suppressing the tremor frequency while causing less distortion of voluntary motion. A time-invariant notch filter is generally unsuitable, because the tremor frequency is unknown and time-varying. We therefore use an adaptive filter, which learns the tremor frequency and amplitude, in order to suppress tremor during human-machine control.

II. METHODS

We have developed the Weighted-frequency Fourier Linear Combiner (WFLC), an adaptive signal processing algorithm which forms a truncated Fourier series model of a periodic signal of unknown frequency and amplitude. The WFLC algorithm is as follows:

$$x_{r_k} = \begin{cases} \sin\left(r\sum_{t=0}^{k} w_{0_t}\right), & 1 \le r \le \mathrm{M} \\ \cos\left((r-\mathrm{M})\sum_{t=0}^{k} w_{0_t}\right), & \mathrm{M}+1 \le r \le 2\mathrm{M} \end{cases}$$

$$\varepsilon_k = s_k' - \mathbf{w}_k^{\mathrm{T}}\mathbf{x}_k$$

$$w_{0_{k+1}} = w_{0_k} + 2\mu_0\varepsilon_k\sum_{i=1}^{\mathrm{M}}\left(w_i x_{\mathrm{M}+i} - w_{\mathrm{M}+i}x_i\right)$$

$$\mathbf{w}_{k+1} = \mathbf{w}_k + 2\mu_1\mathbf{x}_k\varepsilon_k, \tag{1}$$

where $\mathbf{w}_k = [w_{1_k} \ldots w_{2\mathrm{M}_k}]^{\mathrm{T}}$, $\mathbf{x}_k = [x_{1_k} \ldots x_{2\mathrm{M}_k}]^{\mathrm{T}}$, M is the number of harmonics used, s_k' is the noisy input s_k high passed at 1.4 Hz cutoff (for best frequency estimation), and μ_0 and μ_1 are adaptive gain parameters. When M=1, the system essentially operates as an adaptive notch filter, in which the notch frequency is equal to the value of the frequency weight w_{0_k}. The system learns the unknown tremor frequency, tracking its modulation in order to maintain the proper notch frequency. The running sum of w_{0_k} values used to define $\mathbf{x}_k$ is necessary so that crucial phase information is not lost. Actual signal canceling is done by a second set $\hat{\mathbf{w}}_k$ of amplitude weights, which operate on the raw signal s_k, tracking amplitude modulation of the tremor.

$$\hat{\varepsilon}_k = s_k - \hat{\mathbf{w}}_k^{\mathrm{T}}\mathbf{x}_k$$

$$\hat{\mathbf{w}}_{k+1} = \hat{\mathbf{w}}_k + 2\mu\mathbf{x}_k\hat{\varepsilon}_k \tag{2}$$

A bias weight [6] with a separate adaptive gain μ_b is used to minimize distortion of the voluntary component of motion. Filtering via the WFLC is done for each channel of the input device (e.g., pen).

Because the WFLC cancels tremor by forming a truncated Fourier series estimate of it, the algorithm can also be used to quantify tremor, by processing recorded data offline. This does not supplant spectral analysis of tremor, rather, it supplements spectral analysis by providing additional information about time-varying tremor characteristics.

III. RESULTS

A Summagraphics SummaSketch digitizing tablet with a pen-shaped stylus was used as the data input device. M=1 was used for the data presented here. All subjects provided their written consent.

Human-machine control: Figure 1 shows the results of the WFLC processing computer pen input from a male subject, age 84, with essential tremor.

Clinical tremor quantification: Figure 2 presents an example of the use of the WFLC algorithm for offline tremor quantification. An undiagnosed female subject, age 87, drew an Archimedes spiral on the tablet. The tremor frequency and amplitude modulation can be seen in Figures 2(b) and 2(c). Tremor frequency was estimated directly by w_{0_k}. The effective RMS amplitude at each step was calculated:

$$a_{1_k} = \frac{1}{\sqrt{2}}\sqrt{w_{1_k}^2 + w_{2_k}^2} \tag{3}$$

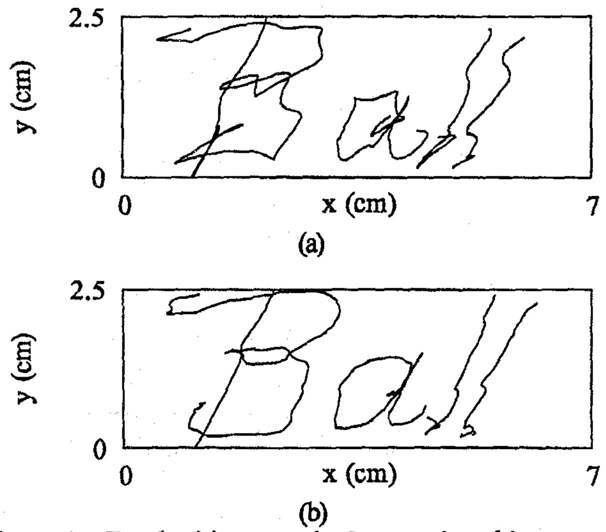

Figure 1. Handwriting sample from male subject, age 84, with essential tremor. μ_1=.005, μ_0=2x10^{-7}, μ_b=.02, μ=.1. (a) Unfiltered. (b) Filtered.

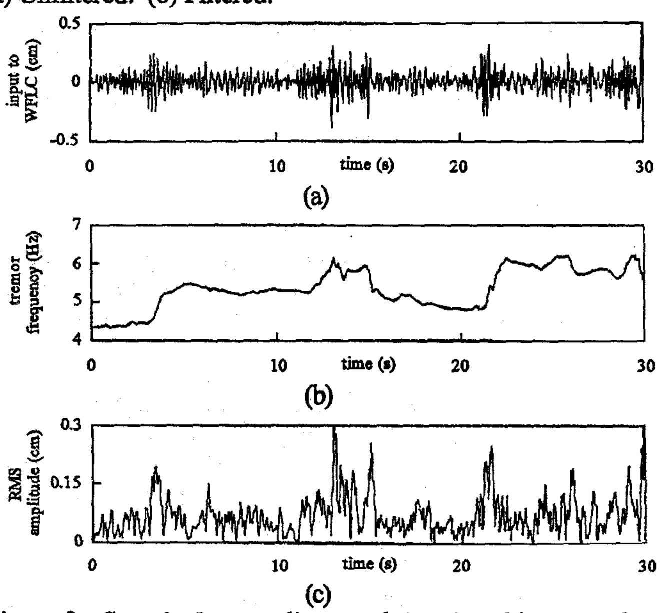

Figure 2. Sample from undiagnosed female subject, age 87. Subject drew an Archimedes spiral. μ_b=.001, μ=.3; μ_0 and μ_1 calculated as functions of input signal power. (a) High-pass filtered input to WFLC. (b) Frequency results. Mean = 5.3 Hz, standard deviation = 0.5 Hz. (c) RMS amplitude results. Mean = 0.07 cm, standard deviation = 0.05 cm.

IV. DISCUSSION

The WFLC is an extension of the Fourier Linear Combiner [7], which models signals of known fundamental frequency. The WFLC is a general method which models periodic signals of unknown frequency and amplitude for any desired number of harmonics. The notch width of the WFLC is proportional to the value of μ. A wider notch provides better canceling of tremor, but also greater distortion of the voluntary component of the signal.

Each different type of pathological tremor (e.g., essential, parkinsonian, cerebellar) usually occupies a certain subband of the overall 2-12 Hz frequency band. The frequency weight w_{0_k} is typically initialized to the center of the nominal subband for the specific type of tremor being canceled. In operation, it is best to allow the system several seconds to adapt to input tremor characteristics when first booted up, before beginning task execution.

The amplitude and frequency of tremor often modulate quite rapidly, requiring a wide notch for effective canceling. For this reason, experiments are also underway with a system in which the WFLC tremor frequency estimation, presented here, is used to adjust the cutoff frequency of an adjustable low pass filter rather than the notch frequency of an adaptive notch filter.

V. CONCLUSIONS

The WFLC is a computationally simple adaptive algorithm which adapts to unknown tremor frequency and amplitude, and tracks modulation of both. Human-machine interfacing for persons with pathological tremor is improved by implementation of the WFLC as a noise estimator and canceler.

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