TREMOR CHARACTERIZATION
Algorithms for the Study of Tremor Time Series

E. Rocon, A. F. Ruiz, J. C. Moreno, J. L. Pons
Bioengineering group, IAI-CSIC, Ctra. Campo Real, km 0.200, Madrid, Spain

J. A. Miranda
Technaid S. L., Madrid, Spain

A. Barrientos
Grupo de Robótica y Cibernética, UPM, Madrid, Spain

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Abstract: This paper introduces the work developed by the authors in the study of tremor time series. First, it introduces a novel technique for the study of tremor. The technique presented is a high-resolution technique that solves most of limitations of the Fourier Analysis (the standard technique to the study of tremor time series). This technique was used for the study of tremorous movement in joints of the upper limb. After, some conclusions about tremor behaviour in upper limb based on the technique introduces are presented. Furthermore, an algorithm able to estimated in real-time the voluntary and the tremorous movement was presented. This algorithm was validated in two contexts with successful results. Finally, some conclusions and future work are given.

1 INTRODUCTION

Tremor is a rhythmic, involuntary muscular contraction characterized by oscillations of a part of the body (Anouti and Koller, 1998). The oscillatory activities are related to various combinations of four basic mechanisms: (a)mechanically induced oscillations, (b) oscillations due to reflexes, (c) oscillations generated by neuronal generators in the central nervous system, (d) oscillations resulting from impaired feedforward and feedback loops.

It is well established that tremorous activity is composed of deterministic and stochastic components, (Timmer et al., 2000). The detection and quantification of tremor are of clinical interest for diagnosis of neurological disorders and objective evaluation of their treatment, (Gao and Wen-wen, 2002). Furthermore, the estimation of tremor is an important stage in systems that aim to control limb oscillations, and also in biofeedback studies. In this regard, estimation techniques have been developed for tremor suppression. Methods based on the Fourier transform (FT) are commonly employed for this purpose, specially because of the similarity between the tremor to a sine wave, (Elble and Koller, 1990). For instance, the weighted Fourier linear combiner (WFLC) characterizes the tremor based on its approximation by a sinusoidal waveform, (Riviere, 1995). Riviere also investigated the application of neural networks to augment manual precision by cancelling involuntary motion. Another example is the extraction of frequency parameters from the power spectrum (based on the FT) of the tremor for classification purposes, (Rocon et al., 2004).

This paper introduces an original study for tremor characterization. First, experiments were performed with 31 patients suffering from tremor diseases in order to study tremor characteristics. The data collected in this experiments were analyzed by means of a novel methodology for the study of tremor time series based on *Empirical Mode Decomposition*. This technique allows an automatic detection of tremorous movement and the study of nonlinear and nonstationary characteristics of tremor, (Rocon et al., 2006). Based on the information provided by this study, a novel algorithm able to estimate in real time and composed by two stages, one for the detection of voluntary movements and other for the estimation of

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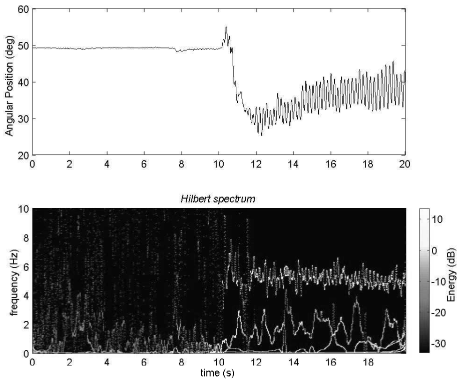

Figure 1: Hilbert Spectrum of an Essential tremor patient performing the task of Keeping the arms outstretched. The high levels of energy activities are perceived when the patient is performing the task.

tremorous movements, is presented. Finally, experiments for the validation of the algorithm presented are given.

2 THE EXPERIMENTAL PROTOCOL

In order to assess tremor characteristics we studied its behavior in 31 patients suffering from different pathologies. The average age of patients was 52.3 years old (ranging from 23 to 84 years old). All patients provided their written consent for the experiments.

The diagnosis of the condition of patients was given by the neurological staff of the General Hospital of Valencia (GHV, Spain) and the functional state of patients was evaluated by means of the Faher scale, (Fahn et al., 1998). Ethical approval for this research has been granted by the Ethical Committee of the GHV.

2.1 Sensors

The tremor was detected by a customized sensor, which is based on the combination of two independent gyroscopes placed distally and proximally to the joint of interest. The joint angular speed is obtained by subtraction of the angular speed measured by one gyroscope from the angular speed measured by the other one. The weight of the system is roughly 15 g, which is a low-mass system when compared to other sensors used in the field, (Rocon et al., 2004). The use of a low-mass sensor is important to reduce the effect of low-pass filtering on the detected signal. Gyroscopes were placed in order to estimate following movements of the upper limb: 1) Elbow flexion-extension, 2) Forearm pronation-supination, 3) Wrist flexion-extension, and 4) Wrist deviation.

2.2 Tasks

Six different tasks were employed for excitation of tremor: 1) Rest, 2) Reaching for an object, 3) Drawing a spiral, 4) Arm outstretched, 5) Touching nose, and 6) Moving a cup. In all tasks the patient was sitting on a chair. This set of tasks aims to stimulate all different types of tremor.

3 ANALYSIS OF TREMOROUS MOVEMENT

In order to analyze the tremorous movement acquired during the experiments, *Empirical Mode Decomposition* was used. This technique was proposed in (Rocon et al., 2006). This technique was identified as a very useful tool for an automatic decomposition of the signal into tremor and voluntary signal. Moreover, this technique enables the representation of the amplitude and the instantaneous frequency of the input signal as function of time in which the amplitude could be contoured on the time-frequency plane. The technique presented is a high-resolution technique that solves most of limitations of the Fourier Analysis (the standard technique to the study of tremor time series). This technique provides, in a time-frequency-energy plot, a clear visualization of local activities of tremor energy over the time, see figure 1.

Based on this technique, a study of the tremorous movement at different joints of the upper limb was developed. The study was performed with the data collect from the experiments introduced in the previous section and aim at understanding tremorous behaviour. The main conclusions of this study are the following: 1)the amplitude of the tremorous movement is larger in distal joints than in proximal joints, 2)the frequency of tremorous movements is comprised in the bandwidth between 3 and 8 Hz, 3)tremor frequency at different joints of the upper limb has very similar values, 4)tremor frequency is not related to the task performed by the patient, 5)the frequency of tremorous movement is constant during the execution of a task, nevertheless it could change during repetitions of the same task, 6)tremor activity is not always present during the experiments. Patients showed tremor activity just during 40% of the time measured, 7) sex and age does not influence tremor behaviour. The main novelty of this study is that it is centered in tremor at joint level while the majority of the studies presented in the literature are centered in the study of tremor at finger tip. The main drawback of this technique is the impossibility to implement it in real-time (RT). In order to address this issue, next section describes the development of an algorithm able to distinguish in RT tremorous movement from voluntary movement.

4 TREMOR ESTIMATION

A number of estimation algorithms have been developed for tremor suppression. As a first approach, we evaluated robust algorithms based on IEEE-STD-1057, which is a standard for fitting sine waves to noisy discrete-time observations. In particular, the weighted-frequency Fourier linear combiner (WFLC) developed by Riviere, (Riviere, 1995), in the context of actively counteracting physiological tremor in microsurgery was implemented. The WFLC is an adaptive algorithm that estimates tremor using a sinusoidal model, estimating its time-varying frequency, amplitude, and phase. The WFLC can be described by equation 1. It assumes that the tremor can be mathematically modelled as a pure sinusoidal signal of frequency ω_0 plus M harmonics and computes the error, ε_k, between the motion, s_k, and its harmonic model.

$$\varepsilon_k = s_k - \sum_{r=1}^{M} [w_{r_k}\sin(r\omega_{0_k}k) + w_{r+M_k}\cos(r\omega_{0_k}k)] \qquad (1)$$

In its recursive implementation, see equations 2 and 3, the WFLC can be used online to obtain estimations of both tremor frequency and amplitude, (Riviere, 1995).

$$w_{0_{k+1}} = w_{0_k} + 2\mu_0\varepsilon_k \sum_{r=1}^{M} r\,(w_{r_k}x_{M+r_k} - w_{M+r_k}x_{r_k}) \qquad (2)$$

where,

$$x_{rk} = \begin{cases} \sin(r\omega_0 k), & 1 \leq r \leq M \\ \cos((r-M)\omega_0 k), & M+1 \leq r \leq 2M \end{cases} \qquad (3)$$

The WFLC algorithm was evaluated with the signals measured in the experiments described in previous section. In the completed trials, the algorithm was able to estimate the tremor movement of all the patients with accuracy always lower than 2 degrees, see figure 2. The main disadvantage of the WFLC is the need for a preliminary filtering stage to eliminate the voluntary component of the movement, (Riviere, 1995). This filtering stage introduces an undesired time lag for our system when estimating tremor movement, this time lag introduces a time delay that could considerably affect the implementation of the control strategies for tremor suppression.

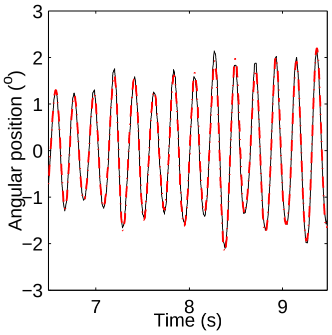

Figure 2: Estimation of tremor, solid line, based on WFLC algorithm, red dashed line.

4.1 Estimation of Voluntary Movement

The tremor literature indicates that voluntary movements and tremor movements are considerably different, (Elble and Koller, 1990). Voluntary movements are slower while tremor movements are brusquer. This indicates that adaptive algorithms to estimate and track movement would be useful when separating the two movements with an appropriate design. The underlying idea is to design the filters so that they only estimate the less dynamic component of the input signal, which in our case we consider to be voluntary movement, thereby filtering out the tremor movement.

A set of algorithms was considered for the estimation of the voluntary motion: two point-extrapolator, critically damped g-h estimator, Benedict-Bordner g-h estimator, and Kalman filter. These algorithms implement both estimation and filtering equations. The combination of these actions allows the algorithm to filter out the tremorous movement from the overall motion at the same time it reduces the phase lag introduced, (Bar-Shalom and Li, 1998). The equation parameters were adjusted to track the movements with lower dynamics (voluntary movement) since tremors present a behaviour characterised by quick movements. The performance of these algorithms were compared based on their accuracy when estimating voluntary movements of tremor time series from patients.

4.1.1 Two Points Extrapolator

It is the simplest tracking algorithm. This algorithm uses the current position measured, y_n, and the past measured position, y_{n-1}, to estimate the velocity, $\dot{x}_n^*$, and the future position x_{n+1}^*.

$$\dot{x}_n^* = \frac{y_n - Y_{n-1}}{T}, \qquad (4)$$

$$x^*_{n+1} = y_n + T * \dot{x}^*_n, \tag{5}$$

where T is the sample time and "$*$" denotes an estimated value.

4.1.2 Critically Damped G-h Estimator

This estimation algorithm is a g-h filter composed by g-h track update equations and by g-h prediction equations

$$update \begin{cases} \dot{x}^*_{k,k} = \dot{x}^*_{k,k-1} + h_k \left(\frac{y_k - x^*_{k,k-1}}{T}\right) \\ x^*_{k,k} = x^*_{k,k-1} + g_k \left(y_k - x^*_{k,k-1}\right) \end{cases} \tag{6}$$

$$predict \begin{cases} \dot{x}^*_{k+1,k} = \dot{x}^*_{k,k} \\ x^*_{k+1,k} = x^*_{k,k} + T\dot{x}^*_{k+1,k} \end{cases} \tag{7}$$

The track update equations or estimation equations, 6, provide us the velocity and position of tremor at time kT after the measurement of the angular position of the joint, y_k. The estimated position is based on the use of the actual measurement as well as the past prediction. As a consequence of filtering, the measured noise is reduced. The predicted position is an estimate of x_{n+1} based on past states and prediction (equation 7), and take into account the current measurement by means of updated states.

4.1.3 Benedict-Bordner G-h Estimator

This estimation algorithm have the same equations that the Critically Damped g-h estimator but with different values in the parameters g-h, (Bar-Shalom and Li, 1998). The Benedict-Bordner estimator is designed to minimize the transient error. Filter g-h parameters are related by:

$$h = \frac{g^2}{2-g} \tag{8}$$

4.1.4 The Kalman Filter

The Kalman filter is a g-h filter where the weights g and h are a function of n and are updated recursively. This filter has the advantage of allowing the optimum use of the information if it is available. In addition, permits the use of the target dynamics information to optimize the filter parameters. More complete information about Kalman filter can be found in (Bar-Shalom and Li, 1998).

4.2 Figure of Merit

In order to quantitative compare the estimators proposed a metric, *Cinematic Estimation Error (CEE)*, was proposed. The equation that define this metrics is:

$$CEE = \sqrt{\varphi^2_{|b^*|} + \sigma^2_{x^*}}, \tag{9}$$

where $\varphi^2_{|b^*|}$ is the mean square of errors of the estimators: $|b^*| = |x_k - x^*_{k,k-1}|$, and $\sigma^2_{x^*}$ variance of the estimation.

CEE quantifies the transient response through $\varphi^2_{|b^*|}$ and, at the same time, the averaging or filtering capabilities of the filter through the term $\sigma^2_{x^*}$. The accuracy and transient response of the estimation algorithms are important. Another important parameter taken into account in our analysis was the execution time of each algorithm in view of the fact that the system was designed to work in real time. The result of such analysis indicated that Benedict-Bordner filter presents the best results with the lowest computational cost.

4.3 Real-time Estimation of Voluntary and Tremorous Movement

The solution adopted was the development of an algorithm capable of estimating voluntary and tremorous motion with a small phase lag based on a two-stage algorithm. In the first stage, the Benedict-Bordner filter estimates the voluntary component of the movements. In the second stage, the estimated voluntary motion is removed from the overall motion and it is assumed that the remaining movement is tremor. After this, the WFLC was used in order to estimate tremor parameters. In this stage, the algorithm estimates both the amplitude and the time-varying frequency of the tremorous movement.

The algorithm proposed was evaluated with data obtained from the patients measured in our experiments. The estimation error of the first stage was 1.4 ± 1.3 degrees. The second stage algorithm has a convergence time always smaller than 2 s for all signals evaluated and the Mean Square Error (MSE) between the estimated tremor and the *real tremor*, after the convergence, is smaller than 1 degree. The combination of both techniques resulted in a very efficient algorithm with small processing cost for estimating in real time the voluntary and the tremorous components of the overall motion.

5 EXPERIMENTS AND RESULTS

The performance of the algorithm proposed was evaluated in two different contexts: 1)Tremor suppression based on exoskeleton devices, and 2)Filtering tremorous movement from PC mouse cursor.

5.1 Tremor Suppression based on Exoskeleton Devices

The algorithm for tremor estimation was incorporated to the WOTAS (Wearable Orthosis for Tremor Assessment and Suppression) active exoskeleton for tremor suppression, (Rocon et al., 2007). In order to evaluate the performance of the device developed to suppress tremor we have planned an experimental phase involving 10 patients suffering from different tremor diseases. During the first clinical trials the algorithm was able to measure and estimate tremor parameters, see Figure 3. The capacity of applying dynamic internal forces to the upper limb for tremor suppression (based on the information provided by the tremor estimation algorithm) was also evaluated. Based on this parameter it was found that the device could achieve a consistent 30% tremor power reduction, with reduction peaks in the order of 80% in the tremor power for patients exhibiting severe tremor, see Figure 3. Moreover, patients related that they felt small influence of the WOTAS device on their intended motion, which indicates a proper functioning of the algorithms proposed in the precious section, (Rocon et al., 2007).

5.2 Filtering Tremorous Movement From PC Mouse Cursor

In these experiments the algorithm was integrated in a device connected between the mouse and the computer that should remove tremorous movements from PC mouse cursor. These experiments were carried out in cooperation with Spanish Foundation of Multiple Sclerosis. Previously to the realization of the experiment, the operation of the system was explained to the user. After, the patient was asked to achieve a comfortable position in the chair and to grab and use the mouse as natural as possible. After a time of adaptation and relaxation, roughly 10 minutes, the patient was asked to perform 2 typical movements when using a computer mouse:

1. **Draw a spiral** - The patient was asked to follow with the cursor of the mouse a path with the form of a spiral drawn on the screen of the computer. The trajectory described by the user is not illustrated in the screen; with this approach it is possible to avoid the attempts of the user to correct the trajectory. The patient just has the reference of the model spiral on the screen. During this tasks the buttons are disabled and the trajectory described by the user was recorded by the software.

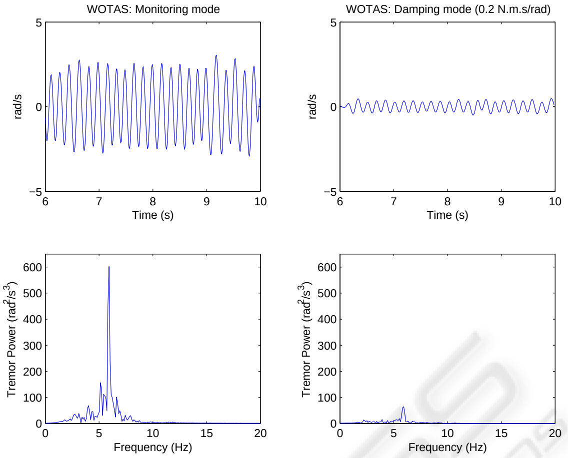

Figure 3: The graphics illustrated the reduction in the tremor power when WOTAS is applying viscosity to the tremorous movement.

2. **Goal and click** - To move the cursor over 10 icons that appear in a random sequence on the screen of the computer.The patient was asked to click over the picture every time he/she reaches it. In this way, the next picture will appear just after the patient click on the actual one. The trajectories and the number of erroneous clicks were recorded.

The total time of each experiment was 40 minutes and the main objective was to quantify the effectiveness of the device in tremor suppression. Each task was repeated 3 times, one with the filter disabled, another one with the filter activated and in the last trial, the filter is deactivated again. The order of trials was randomized. The figures of merit used to quantify the improvement in the ability of the patient in the realization of the tasks were:

1. The relation between the number of times the user leaves the boundaries of the path defined by the spiral, with and without the help of the algorithms, in the task *draw a spiral*, e_s.
2. The relation between the number of erroneous clicks, with and without the help of the algorithms, during the *click and goal* task, e_c.

Table 1: Results of the experiments.

Patient	e_s	e_c
1	20 %	44 %
2	33 %	100 %
3	30 %	28 %
4	50 %	33 %

Table 1 summarizes the results obtained in the data analysis. The results show that all patients improved their performance using the algorithm. In the

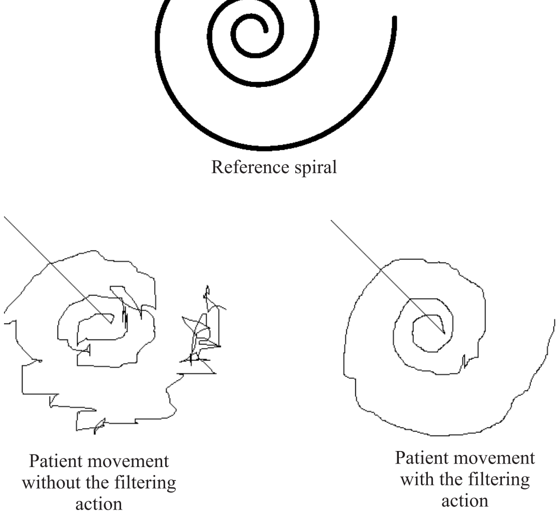

Figure 4: Results of a patient performing the task of drawing a spiral.

case of the *draw a espiral* task, the mean reduction in the error during the realization of the task was in order of 33,3%. This is a sign of a improvement of the patient ability in tracking a shape in the screen. The patients also presented a mean reduction of 52 % in the number of erroneous clicks during the execution of the *goal and click* task. These results indicates a consistent improvement in the ability of the patient in the execution of the tasks, see Figure 4. During the trials it was noticed that feedback of a smooth movement has a positive impact. Two patients spontaneously related that they felt a decrease in the amplitude of their tremorous movement.

6 CONCLUSIONS

This paper summarizes the work developed by the authors in the study of tremor time series. First, it introduces a novel technique for the study of tremor. The main advantage of this technique it that it allows an automatic estimate of the tremulous movement for different pathologies. The technique presented is a high-resolution technique that solves most of limitations of the Fourier Analysis (the standard technique to the study of tremor time series). This technique provides, in a time-frequency-energy plot, a clear visualization of local activities of tremor energy over the time.

The technique was used for the study of tremorous movement in joints of the upper limb. This study generates some conclusions about tremor behaviour in upper limb.

Furthermore, an algorithm able to estimated in real-time the voluntary and the tremorous movement was presented. This algorithm was validated in two contexts with successful results. The algorithm introduced presents a learning behavior that adapts to personal characteristics of each user. This algorithm was implemented in a novel device able to filter tremorous movement from a mouse cursor before it reaches computer interface. The device was successfully tested with patients. The results of the experiments showed an improvement of the patient ability in tracking a shape in the screen and a consistent improvement in the ability of the patient in the accomplishment of tasks, for instance, the number of erroneous clicks was reduced in 52%.

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