TREMOR SUPPRESSION THROUGH FORCE FEEDBACK

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Abstract

This paper presents a method for designing non-adaptive force feedback tremor suppression systems that achieve a specified reduction in tremor energy. Position, rate, and acceleration feedback are examined and two techniques for the selection of feedback coefficients are discussed. Both techniques require the development of open-loop human-machine models through system identification.

It is demonstrated that non-adaptive force feedback tremor suppression systems can be successfully designed when accurate open-loop human-machine models are available.

1. Introduction

Tremor is an involuntary, rhythmic, oscillatory movement of the body [2]. Tremor movements are typically categorized as being either physiological or pathological in origin. Physiological tremor pervades all human movements, both voluntary and involuntary, and is generally considered to exist as a consequence of the structure, function, and physical properties of the neuromuscular and skeletal systems [13]. Its frequency varies with time and lies between 8 and 12 Hz. Pathological tremor arises in cases of injury and disease and is typically of greater amplitude and lower frequency than physiological tremor. In its mildest form, pathological tremor impedes the activities of daily living and hinders social function. In more severe cases, tremor occurs with sufficient amplitude to obscure all underlying voluntary activity [1, 3].

The medical and engineering research communities have invested considerable time and effort in the development of viable physiological and pathological tremor suppression technologies. Physiological tremor suppression is of particular value in applications

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such as teleoperation and microsurgery where slight rapid movements, whether voluntary or involuntary, can have far reaching consequences. Pathological tremor suppression is generally motivated by a desire to improve the quality of life for individuals stricken with abnormal tremor conditions.

A number of digital filtering algorithms have been developed for the purpose of removing unwanted noise from signals of interest and have thus found application in tremor suppression. Riviere and Thakor have investigated the application of adaptive notch filtering for the purpose of suppressing pathological tremor noise during computer pen input [10, 11]. When a reference of the noise signal is available, adaptive finite impulse response (FIR) filters can produce a closed-loop frequency response very similar to that of an adaptive notch filter [14]. Gonzalez et al. developed a digital filtering algorithm that utilized an optimal equalizer to equilibrate a tremor contaminated input signal and a target signal that the subject attempted to follow on a computer screen [6]. Inherent human tracking characteristics, such as a relatively constant temporal delay and over and undershoots at target trajectory extrema, were incorporated in a “pulled-optimization” process designed to minimize a measure of performance similar to the squared error of the tracking signal.

Force feedback systems implement physical intervention methodologies designed to suppress tremor behavior. Several projects have investigated the application of viscous (velocity dependent) resistive forces to the hand and wrist of tremor subjects for the purpose of suppressing tremor movements [3, 4, 12, 14]. Experimentation with varying levels of velocity dependent force feedback showed, qualitatively, that tremor movements could be increasingly suppressed with increasing levels of viscous force feedback, but that concurrent impedance of voluntary movement may occur.

Previous investigations into non-adaptive force feedback tremor suppression systems have not utilized quantitative performance criteria during the design of the feedback control system. They addressed the question of whether or not velocity dependent resistive forces (damping) could effectively suppress tremor movements, but were not concerned with achieving a specified statistical reduction in the tremor. Additionally, the possibility of incorporating position and acceleration feedback to achieve improved performance was not addressed in these studies.

The objective of this research was the development of a methodology that incorporates quantitative performance criteria as well as position, rate, and acceleration feedback into the design of a non-adaptive force feedback tremor suppression system. The remainder of this paper is divided into five sections. Section 2 presents the results of an analysis of pathological tremor movements. The design process for the force feedback system is described in Section 3. Next, a method of system identification for the human-machine system is discussed. Section 5 presents the results of an evaluation of the force feedback system. Finally, the paper is completed with a brief discussion and concluding remarks.

2. Analysis of Tremor Movements

An investigation into the spatio-temporal characteristics of tremor movements was performed to gain insight into the spatial distribution and time-frequency properties of pathological tremor movements. Previous investigations into tremor frequency have typically applied the Fast Fourier Transform (FFT) algorithm to a sampled data sequence to obtain information regarding the exact frequency content of the data. However, no information with respect to the evolution of the frequency content over time is generated with the FFT. It is for this reason that a time-frequency analysis of pathological tremor movements was undertaken. The spatial distribution of tremor movements was also examined. A tremor suppression system could potentially take advantage of unique temporal and spatial distributions in the tremor.

Experimental Design

A broad set of experiments was developed to examine the pertinent tremor characteristics. Five tremor subjects ages 18 to 91 participated in the study.

The tremor subjects were qualitatively categorized with respect to the severity of their tremor. Two subjects possessed the ability to write in a somewhat legible manner and received a low severity label. Relatively large tremor amplitude that prevented legible writing was observed in two of the subjects. The remaining tremor subject exhibited high variability in tremor amplitude and, as such, received a variable severity label. The origin of the tremor in subjects B, D, and E was unknown because no medical diagnosis was available.

The subjects performed target-tracking tasks while seated in front of a 17” computer display. The position of an on-screen cursor was controlled by manipulating a stylus attached to the end-effector of the PHANToM, a small robotic arm used in haptic interfaces.

Table 1. Subject information.

Subject	Age	Gender	Tremor Severity	Source
A	18	M	Var.	Head injury
B	72	M	Mod.	?
C	71	M	Mod.	Parkinson’s
D	80	F	Low	?
E	91	M	Low	?

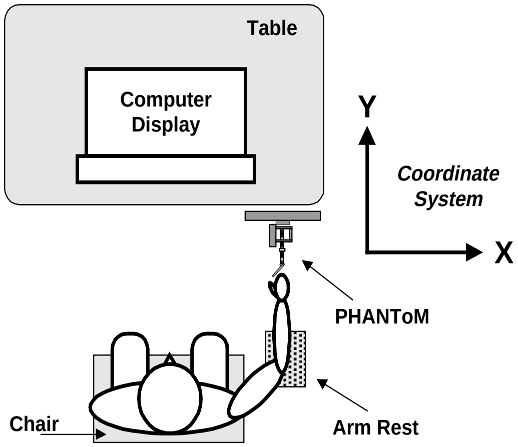

Figure 1. Experimental Setup.

A target tracking task required the subject to follow an on-screen target with a cursor as it propagated along a displayed straight line or sinusoidal pattern. The horizontal position of the PHANToM's end-effector controlled cursor location in a manner analogous to computer mouse input. Pattern orientation, shape, and size as well as target velocity were systematically varied across a number of trials. End-effector position was sampled at 100 Hz throughout each task.

Data Analysis

The frequency content of the tremor subjects' movements was estimated using both Welch's average periodogram method as well as the Short-Time Fourier Transform. Tremor frequencies were selected as those frequencies at which the energy distribution contained a distinct peak. The spatial distribution of the tremor movements was calculated by first isolating the higher frequency tremor "noise" component with a 5th order IIR highpass filter and then counting the number of data points within each cell of a two dimensional mesh.

Results

As shown in Table 2, little variation was observed in the tremor frequencies across the various target tracking tasks when Welch's average periodogram method was employed to find the spectral energy of the movement over the entire task time interval. Subject C consistently exhibited tremor with two distinct frequency components and subject A's tremor was by far the most variable and possessed a rather broad distribution of energy with a mild peak.

Each category of tremor (low, moderate, and variable) exhibited a unique time-frequency relationship, as illustrated in Figure 2. The level of color on the plot indicates the intensity of the movement at a particular time and frequency. Coloration observed at or below approximately 1 Hz represents the voluntary movement and that above 1 Hz can be attributed to tremor movement. A constant frequency and magnitude characterized the moderately severe tremor

Table 2. Mean tremor frequencies.

Subject	[Hz] Mean Freq.	[Hz] Variance
A	3.61	0.21
B	4.03	0.03
C	4.79, 8.78	0.03, 0.06
D	5.04	0.01
E	5.02	0.01

movements of subjects B and C (Figure 2.A). Low severity tremor (Figure 2.B) occurred at a relatively constant frequency but with variable magnitude during the task. Subject A’s tremor was highly variable (Figure 2.C).

The spatial distribution of tremor movements was found to be non-uniform for all of the subjects. In general, the spatial distributions were highly elliptical, indicating a predominant direction of tremor movement.

Three conclusions regarding pathological tremor characteristics were made based on the results of the target tracking tasks: 1.) Tremor frequency is relatively invariant with respect to the direction and speed of movement. 2.) Tremor frequency during task performance is relatively constant, but the intensity, or amplitude, of the tremor may vary. 3.) Tremor movements possess non-uniform spatial distributions.

The conclusions stated above suggest that the methodology behind the design of a force feedback tremor suppression system can include the assumption of a constant tremor frequency.

3. Modification of the Human-Machine Frequency Response

The open-loop properties of the human-machine system are modeled with a

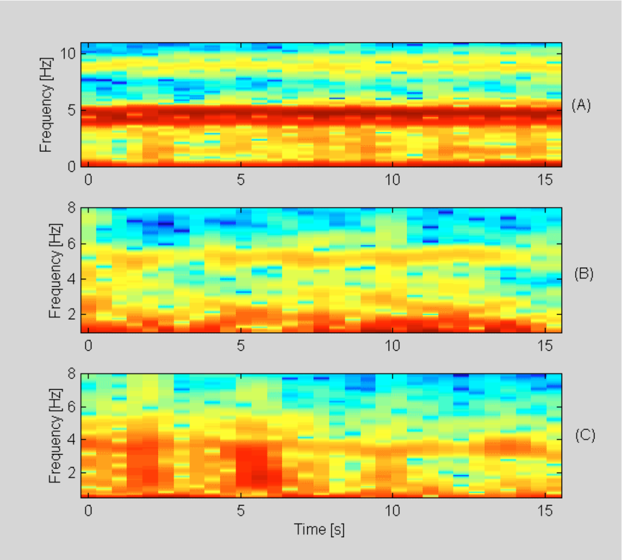

Figure 2. Time-frequency plots. A.) Moderate tremor. B.) Low tremor. C.) Variable tremor.

linear second order time-invariant transfer function, as shown in the forward path of Figure 3. The plant possesses a mass M, damping C, and stiffness K that represent the combined properties of the human limb and the robotic arm as viewed at the end-effector of the PHANToM. This approach was motivated by the work of Dolan et al. and Hollerbach on the impedance characterization of the human arm [5, 7].

Second order negative feedback was generated by the manipulator to create the closed-loop system depicted in Figure 3 which has the transfer function

$$T(s) = \frac{1}{(M+a_1)s^2 + (C+a_2)s + (K+a_3)} \quad (1)$$

The feedback coefficients a_1, a_2, and a_3 impact the effective mass, damping, and stiffness of the closed-loop system in an additive fashion. The magnitude response of the closed-loop system is a function of the plant parameters M, C, and K as well as the feedback coefficients and can be expressed as

$$R_\omega = \frac{1}{\sqrt{\left[K + a_3 - \left(M + a_1\right)\omega^2\right]^2 + \left(C + a_2\right)^2 \omega^2}} \quad (2)$$

The feedback coefficients are selected to increase the attenuation at a specified tremor frequency and preserve the low frequency magnitude response of the open-loop system. Figure 4 illustrates the design methodology where the closed-loop system produces a desired attenuation A_d at a designated tremor frequency ω_t but does not introduce additional attenuation at frequencies below a designated passband frequency ω_p. This tremor suppression technique is not well suited for individuals whose tremor frequency lies very close to voluntary movement frequencies.

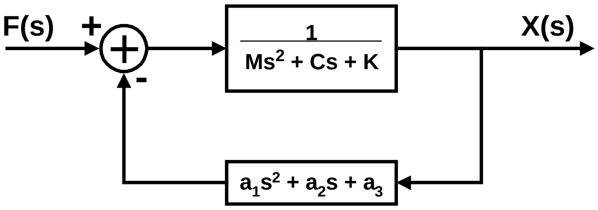

Figure 3. Closed-loop human-machine system with 2nd order feedback.

Setting ω to zero in Equation (2), reveals that a nonzero position feedback coefficient a_3 will introduce undesirable low frequency attenuation in the closed-loop system. For this reason, the position feedback coefficient a_3 is set to zero.

The first technique for selecting the feedback coefficients permits the selection of either the rate or acceleration feedback coefficient. First, the open-loop magnitude response of the human-machine system at a tremor frequency ω_t is determined by evaluating Equation (1) with estimates of the plant parameters and zero feedback. Next, a desired level of closed-loop attenuation for movements at the tremor frequency is selected and used to evaluate one of the following expressions depending on whether acceleration (a_1) or rate (a_2) feedback is desired.

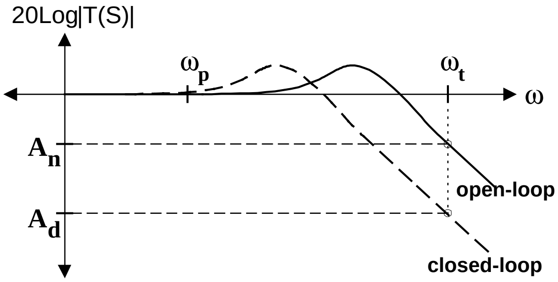

Figure 4. Illustration of the magnitude response modification technique. The closed loop system increases the attenuation at the tremor frequency while ideally not impeding lower frequency voluntary movements.

$$a_1 = \frac{1}{\omega_t^2}\left[K + \sqrt{\left(\frac{1}{R_{\omega_t}}\right)^2 - C^2\omega_t^2}\right] - M \quad (3)$$

$$a_2 = \frac{1}{\omega_t}\sqrt{\left(\frac{1}{R_{\omega_t}}\right)^2 - \left(K - M\omega_t^2\right)^2} - C \quad (4)$$

The second technique for selecting the rate and acceleration feedback coefficients directly addresses the issue of preserving the low frequency magnitude response of the open-loop human-machine system. In this case, two additional frequency-attenuation pairs are selected: the zero frequency gain of the open-loop system and the open-loop attenuation at a frequency ω_p that represents the highest frequency for which the closed-loop magnitude response should approximate the open-loop magnitude response (see Figure 4). A general least-squares fitting algorithm is used to select the feedback coefficients that will produce a closed-loop magnitude response that is a least-mean-square approximation to the desired response described by the frequency-attenuation pairs.

4. System Identification

The apparent mass, damping, and stiffness of the open-loop human-machine system are required in order to select the appropriate rate and acceleration feedback coefficients. These parameters were estimated by approximating the frequency response of a discrete-time auto regressive moving average (ARMA) human-machine model with that of a second order continuous-time model.

To generate the ARMA model of the human-machine system, a band-limited zero-mean white noise force profile was applied by the manipulator while the tremor subject grasped the attached stylus. The resulting movement profile was then sampled at 1 kHz and filtered using an adaptive FIR filter to remove the active tremor component that does not arise from the physical properties of the system. Next, the *least-squares modified Yule-Walker method* was employed to determine the coefficients of the ARMA model [9]. The discrete-time frequency response of the ARMA model was then mapped, in a least-squares sense, to a second order continuous-time model.

5. Results

The tremor suppression technique described in Section 3 was evaluated on three tremor subjects C,D, and E, as subject B was unavailable and the variable tremor of subject was not suitable for evaluation. The experimental setup was identical to that during the target-tracking tasks. Open-loop human-machine models were developed, as described above, and suitable feedback coefficients were calculated. Next, the force feedback controller was implemented using the robotic manipulator and ability of the system to create the desired tremor reduction was evaluated.

Tables 3, 4, and 5 present the estimated mass, damping, and stiffness values. These values represent the combined parameters of both the human and the robotic arm. Subjects A and C, who possessed the most severe tremor, also exhibited the greatest stiffness (i.e. rigidity).

Once the open-loop human-machine models were developed, the feedback coefficients required to produce 10 dB and 20 dB of tremor attenuation were calculated. Three feedback configurations were examined: strictly rate feedback, strictly acceleration feedback, and the coexistence of rate and acceleration feedback (via the least-squares method). It was found that the level of damping required for the "strictly rate feedback" configuration designed to generate 20 dB of tremor attenuation was prohibitively large. For this reason, the ability of the system to create 20 dB of tremor attenuation using strictly rate feedback was not evaluated.

The tremor subjects were asked to grasp the stylus attached to the end-effector and manipulate it slowly throughout the entire workspace. The force feedback configurations were individually implemented and applied during separate trials. During each trial, the robotic arm operated at 1 kHz.

The reduction in the tremor movement power was used as a measure of the tremor attenuation achieved through the force feedback. Table 6 shows the average levels of tremor attenuation achieved with each feedback configuration. When a 10 dB reduction in tremor amplitude was sought, rate feedback provided, on average, the best performance. The coexistence of rate and acceleration feedback provided the best performance when 20dB of tremor attenuation was sought.

Table 3. Mass estimates for the open-loop human-machine system [Kg].

Subject	X	Y	Z
A	0.547	0.505	1.176
C	0.568	1.073	0.772
D	0.245	0.286	0.292
E	0.249	0.736	0.292

Table 4. Damping estimates for the open-loop human-machine system [Ns/m].

Subject	X	Y	Z
A	4.969	15.317	28.819
C	6.121	10.913	19.646
D	4.189	8.515	7.281
E	7.556	16.219	8.356

Table 5. Stiffness estimates for the open-loop human-machine system [N/m].

Subject	X	Y	Z
A	190.335	312.758	219.873
C	264.673	300.219	283.694
D	16.637	213.570	186.215
E	47.824	68.562	53.293

Table 6. Avg. tremor energy reduction [dB]

Feedback Config.	Goal: 10dB attenuation	Goal: 20dB attenuation
Rate	10.679	(not tested)
Acceleration	7.752	14.391
Rate & Accel.	8.811	15.073

Figure 5 shows subject C's performance on a pattern-tracing task. A desired spatial trajectory was displayed on the computer screen and the subject was instructed to trace the pattern with a cursor controlled through manipulating the stylus. Both rate and acceleration feedback were applied in an attempt to achieve 20 dB of tremor attenuation.

6. Discussion & Conclusions

Two techniques for the design of non-adaptive force feedback tremor suppression systems have been developed. Both methods utilize quantitative frequency domain performance criteria during the selection of the gain in rate and acceleration feedback pathways. The issue of preserving voluntary movement in the presence of adequate tremor suppression can be addressed when both rate and acceleration feedback exist simultaneously.

The ability of the force feedback to produce a desired level of tremor attenuation depends on the accuracy of the parameters in the open-loop human-machine model. Only the average impedance of the human arm was characterized in this research and, for this reason, localized inaccuracies of the human-machine models may exist and lead to degraded performance. Additionally, the reflex behavior and force-velocity properties of the muscles in the human arm have not been considered.

It is suggested that future investigations utilize adaptive second order feedback that seeks an “optimal” level of tremor reduction. Additionally, higher order feedback systems could provide improved performance but may suffer from significant noise amplification and instability problems.

In conclusion, it has been demonstrated that a non-adaptive force feedback system can be designed such that movements at a designated frequency experience a specified level of attenuation. When second order feedback is present, additional frequency domain constraints, such as the preservation of lower frequency voluntary movements, can be addressed.

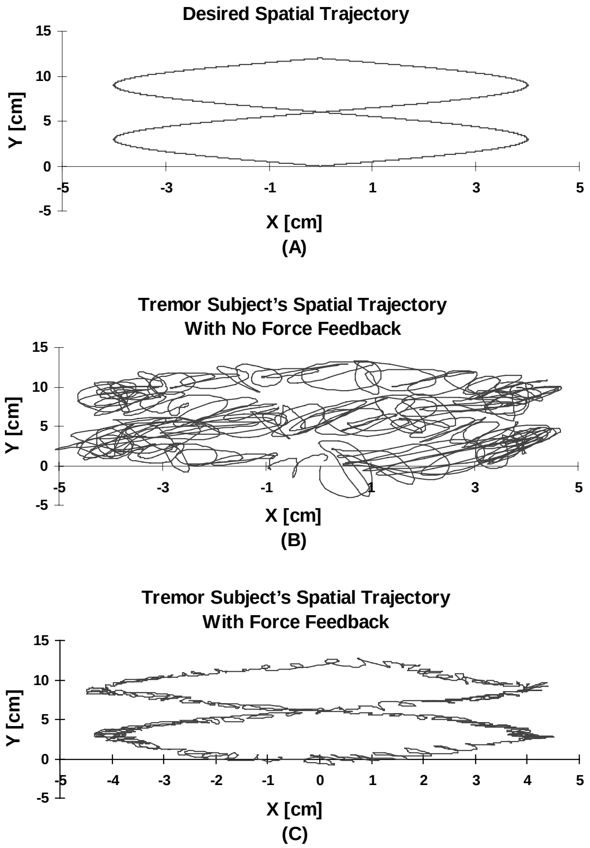

Figure 5. Qualitative example showing the effect of force feedback on pattern tracing performance. A.) Desired spatial pattern. B.) Performance without force feedback. C.) Improved performance with force feedback.

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