INTELLIGENT ACTIVE FORCE CONTROL OF HUMAN HAND TREMOR USING SMART ACTUATOR

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To my lovely spouse

Siti Nur Zulaikha binti Mohamad Rasid

To my beloved parents

Allahyarham As'arry bin Johari

Jamilah binti Sahminan

To my elder brother

Allahyarham Azizi bin As'arry

To my younger sister

Azizahani binti As'arry

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ABSTRACT

Patients suffering from Parkinson's disease (PD) experience tremor which may generate a functional disability impacting their daily life activities. In order to provide a non-invasive solution, an active tremor control technique is proposed to suppress a human hand tremor. In this work, a hybrid controller which is a combination of the classic Proportional-Integral (PI) control and Active Force Control (AFC) strategy was employed. A test-rig is utilized as a practical test and verification platform of the controller design. A linear voice coil actuator (LVCA) was utilized as the main active suppressive element to control the tremor of hand model in collocation with the sensor. In order to validate the AFC scheme in real-time application, an accelerometer was used to obtain the measured values of the parameter necessary for the feedback control action. Meanwhile, a laser displacement sensor was used to quantify the displacement signal while hand shaking. To optimize the controller parameters, three different optimization techniques, namely the genetic algorithm (GA), particle swarm optimization (PSO) and differential evolution (DE) techniques were incorporated into the hybrid PI+AFC controller to obtain a better performance in controlling tremor of the system. For the simulation study, two different models were introduced to represent the human hand in the form of a mathematical model with four degree-of-freedom (4 DOF) biodynamic response (BR) and a parametric model as the plant model. The main objective of this investigation is to optimize the PI and AFC parameters using three different types of intelligent optimization techniques. Then, the parameters that have been identified were tested through an experimental work to evaluate the performance of controller. The findings of the study demonstrate that the hybrid controller gives excellent performance in reducing the tremor error in comparison to the classic pure PI controller. Based on the fitness evaluation, the AFC-based scheme enhances the PI controller performance roughly around 10% for all optimization techniques. Besides that, an intelligent mechanism known as iterative learning control (ILC) was incorporated into the AFC loop (called as AFCAIL) to find the estimated mass parameter. In addition, a sensitivity analysis was presented to investigate the performance and robustness of the voice coil actuator with the proposed controller in real-time environment. The results prove that the AFCAIL controller gives an excellent performance in reducing the hand tremor error in comparison with the classic P, PI and hybrid PI+AFC controllers. These outcomes provide an important contribution towards achieving novel methods in suppressing hand tremor by means of intelligent control.

ABSTRAK

Pesakit yang menderita dari penyakit Parkinson mengalami getaran dimana menyebabkan ketidakupayaan fungsi dalam menjalani kehidupan harian. Bagi menyediakan penyelesaian secara tak invasif, teknik kawalan getaran aktif dicadangkan untuk mengurangkan getaran pada model tangan manusia. Dalam kerja ini, kawalan berkembar dimana gabungan klasik kawalan kamiran-berkadaran (PI) dan strategi Kawalan Daya Aktif (AFC) digunakan. Sebuah alat ujikaji digunakan sebagai ujian peringkat amali dan platform pengesahan bagi rekabentuk kawalan. Sebuah penggerak gegelung suara lelurus (LVCA) digunakan sebagai elemen utama dalam pengurangan aktif untuk mengawal getaran pada model tangan dalam keadaan selari dengan penderia. Bagi pengesahan skim AFC dalam aplikasi masa sebenar, sebuah meter pecut digunakan untuk mengukur parameter yang sesuai untuk maklumbalas tindakan kawalan. Sementara itu, sebuah penderia jarak laser digunakan untuk mengukur isyarat jarak ketika tangan bergetar. Bagi mengoptimumkan parameter kawalan, tiga teknik pengoptimuman dinamakan sebagai algoritma genetik (GA), pengoptimuman kerumunan zarah (PSO) dan pembezaan evolusi (DE) teknik telah digabungkan ke dalam kawalan hibrid PI+AFC untuk mendapatkan prestasi yang lebih baik dalam mengawal getaran sistem. Untuk kajian simulasi, dua model yang berbeza diperkenalkan untuk mewakili tangan manusia dalam bentuk model matematik dengan empat darjah kebebasan (4DOF) respon biodinamik (BR) dan sebuah model parametrik sebagai model pelan (model yang dikawal). Objektif utama kajian ini adalah untuk menganggarkan parameter PI dan AFC, menggunakan tiga jenis teknik pengoptimum pintar yang berbeza. Kemudian, parameter yang telah dikenalpasti akan diuji dalam kerja eksperimen untuk menilai prestasi pengawal. Hasil kajian menunjukkan bahawa pengawal hibrid memberi prestasi yang sangat baik dalam mengurangkan gegaran berbanding dengan pengawal PI klasik. Berdasarkan penilaian kecergasan, skim berasaskan AFC meningkatkan prestasi pengawal PI sebanyak lebih kurang 10% untuk semua teknik pengoptimuman. Selain itu, satu mekanisme yang bijak, dikenali sebagai lelaran kawalan pembelajaran (ILC) dimasukkan ke dalam gelung AFC (dipanggil sebagai AFCAIL) untuk mencari parameter anggaran berat. Di samping itu, analisis sensitiviti dibentangkan untuk menyiasat prestasi penggerak gegelung suara dan keteguhan pengawal yang dicadangkan dalam persekitaran masa sebenar. Hasil kajian menunjukkan pengawal AFCAIL memberikan prestasi cemerlang dalam mengurangkan gegaran tangan berbanding dengan menggunakan kawalan klasik P, PI dan hibrid PI + AFC. Hasil kajian ini memberi sumbangan yang penting kepada para penyelidik demi untuk mendapatkan kaedah sesuai untuk mengurangkan gegaran tangan dengan menggunakan kawalan pintar.

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LIST OF ABBREVIATIONS

A/D	-	Analogue to Digital
AFC	-	Active Force Control
AFCAIL	-	Active Force Control and Iterative Learning
ARMAX	-	Auto-regressive Moving Average with Exogenous
ARX	-	Auto-regressive with Exogenous
BR	-	Biodynamic Response
CAD	-	Computer Aided Design
CNS	-	Central Nervous System
CPU	-	Control Processing Unit
D/A	-	Digital to Analogue
DAQ	-	Data Acquisition Card
DBS	-	Deep Brain Stimulation
DC	-	Direct Current
DE	-	Differential Evolution
DOF	-	Degree of Freedom
DRIFT	-	Dynamics Responsive Interventions for Tremor Suppression
DVB	-	Double Viscous Beam
EM	-	Estimate Mass
ET	-	Essential Tremor
FFT	-	Fast Fourier Transformation
GA	-	Genetic Algorithm
IAE	-	Integral of Absolute Error
ILC	-	Iterative Learning Control
LCAM	-	Linear Current Amplifier Module
LS	-	Least Square
LVCA	-	Linear Voice Coil Actuator
LVDT	-	Linear Variable Differential Transformer

MEMS	-	Micro Electromechanical Systems
MLE	-	Maximum Likehood
MPDA	-	Malaysia Parkinson's Disease Association
MR	-	Magneto Rheological
MSE	-	Mean Square Error
OSA	-	One step-ahead
OVAT	-	One Value at A Time
PCI	-	Peripheral Interface Circuit
PD	-	Parkinson's Disease
PEM	-	Prediction Error Method
PFC	-	Piezoelectric Fibre Composite
PI	-	Proportional-Integral
PID	-	Proportional-Integral-Derivative
PRBS	-	Pseudo Random Binary System
PSD	-	Power Spectral Density
PSO	-	Particle Swarm Optimization
PZA	-	Piezoeletric Actuator
RLS	-	Recursive Least Square
SI	-	System Identification
SMA	-	Shape Memory Alloy
SUS	-	Stochastic Universal Sampling
TVA	-	Tuned Vibration Absorber
WOTAS	-	Wearable Orthosis for Tremor Assessment and Suppression

LIST OF SYMBOLS

f	-	Force
$f(x)$	-	Function of variable x
l	-	Length
m	-	Mass
c	-	Damper
c_1, c_2	-	Acceleration Constant
$\varepsilon(t_{i-1})$	-	Prediction error
k	-	Spring
t	-	Time
ω	-	Inertia weight
v_{k+1}^{i}	-	Velocity of particle swarm
x_{k}^{i}	-	Position of particle swarm
$v_{i,D}^{g}$	-	Mutant vector for DE
$u_{i,D}^{g}$	-	Trial vector for DE
$x_{i,D}$	-	Target vector for DE
$y(t_i \mid x)$	-	System output
$\hat{y}(t_i \mid x)$	-	Predictor output
ϕ	-	Regressors
$\phi_{\varepsilon\varepsilon}(\tau)$	-	Auto-correlation test
$\phi_{u\varepsilon}(\tau)$	-	Cross-correlation test
Cr	-	Crossover rate for DE
D	-	Problem dimension
F	-	Differentiation constant
G_{best}^{k}	-	Global best

Hz	-	Frequency unit
K_P	-	Proportional gain
K_I	-	Integral gain
L_D	-	Lower boundary
H_D	-	Higher boundary
M'	-	Estimation mass
Np	-	Population size
P_c	-	Crossover rate for GA
P_m	-	Mutation rate for GA
P_{best}^{k}	-	Personal best
Q’	-	Estimated disturbance

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

In recent years, biomechanics has played a pivotal role in improving human movement, for example with regard to the mechanical properties of soft tissue and bones, orthopaedic implants for human joints, the study of human 3D motion, gait motion, rehabilitation and injury prevention. The use of an engineering mechanics approach in medical systems promotes better quality of life in people with disabilities. In addition, information sharing and technology transfer between both disciplines creates more excellent intellectual property that gives benefits to human life. This study is related to the biomechanics of human movement and concerns to help patients with severe tremors or shaking of the hand. The hands are an interesting subject with regard to control, due to their ability and multi-functioning; for example, grasping objects, writing, cutting things or other normal human hand activities that need to be done precisely. Therefore, this study attempts to promote a mechanical-based non-invasive treatment by developing a suitable scheme for active tremor control. Smart actuator such as piezoelectric actuator (PZA), shape memory alloy (SMA) or magneto rheological fluid (MRF) is possibly applied for an actuation system based on their performance profile. However, this project used linear voice coil actuator (LVCA) type as an actuator to suppress hand tremors. Some advantages of using LVCA are its silent operation, smooth, backlash-free motion, relatively low cost and easily controlled.

In this thesis, an online method of the hybrid proportional-integral (PI) control with active force control (AFC) strategy for tremor attenuation is presented. An intelligent mechanism using iterative learning control (ILC) is incorporated into the AFC loop to approximate the estimation mass (EM) parameter. In order to have a valid AFC scheme in actual applications, accelerometer was used to obtain the measured values of the necessary parameters and the feedback control action. Meanwhile, laser displacement sensor is used to measure the displacement signal of tremor behaviour precisely. The integration of sensors and actuator with the proposed control strategies produces an active tremor control device.

For the experimental study, an available experimental rig (Zain *et al.*, 2010) was modified so that the rig was able to emulate actual human hand tremor behaviour. Hence, the performance of smart actuators in attenuating hand tremors with the proposed controller were investigated and evaluated. Experiments were conducted on a dummy hand model that was placed horizontally in a tremor test rig. When activated by a shaker in the vertical direction, this resembles a postural tremor condition. Sensitivity analysis is presented to investigate the robustness of the proposed controller in a real-time control environment.

In the simulation environment, a mathematical model of a four degree-of-freedoms (4-DOF) system was introduced to represent the biodynamic response (BR) of the palm of a human hand. An identification method was used to model and identify the transfer function model of tremor behaviour for the dummy hand. A closed loop control, consisted of a classic PI control and AFC scheme, was used to control a linear transfer function of voice coil actuator to attenuate the 4-DOF hand tremor and identification of the plant model. Here, the hybrid type control scheme with three optimisation techniques: a) Genetic Algorithm (GA) b) Particle Swarm Optimisation (PSO) and c) Differential Evolution (DE), were used to optimise the PI parameters and estimate mass parameters in the AFC scheme, the goal of which was to find the minimum fitness function (approach to zero tremor error). These optimisations were selected due to their capabilities in achieving high efficiency in searching for global optimal solutions. Although all techniques are able to compute fitness function and find optimal solutions, the different strategies and computational efforts among them will be discussed and compared in terms of performance. Finally, the results of simulations and experiments were validated and compared in terms of displacement and acceleration amplitude (error) of hand tremor oscillations in time domains and also after conversion to frequency domains.

1.2 Research Background

Parkinson’s disease (PD) is a progressive neurodegenerative disease, often characterised by tremor, slowness of movement, difficulty maintaining balance, and muscle rigidity. About two-third of Parkinson’s disease patients suffer from tremor or unintentional movement in one or more parts of the body. Tremors most commonly occur in the hand; however, they may affect the head, face, vocal cords, trunk, and legs. Debilitating conditions of hand tremors may interfere with a patient’s daily activities, such as eating, writing and holding objects. Thus, it may cause some frustration that can affect their moods, which may in turn erode their quality of life. In addition, the person also feels embarrassed to face other people and often prefer to stay at home rather than go outside. There are no official statistical data available on people experiencing severe Parkinson disease in Malaysia. According to the Malaysian Parkinson’s Disease Association (MPDA), it is estimated that about 15,000 to 20,000 PD sufferers in Malaysia. As there is no cure for PD currently available and the proportion of elderly people in the population is increasing, the total number of PD patients is expected to rise to between 25,000 and 30,000 by the year 2020 (Lai, 2009).

Experts in the field of tremor also agree that no medication approach can cure hand tremors (Archibald and Burn, 2008; Bhidayasiri, 2005; Rocon *et al.*, 2004). While long-term drug taking may cause negative side effects (Poewe, 2010) and surgical technology may appear to be the best treatment, it is a very costly and high risk treatment (Ford, 2008). Among the estimated 15,000 Parkinson’s disease patients in Malaysia, about 1000 of them require high risk surgery, namely Deep Brain Stimulation (DBS) surgery, to survive (Kong, 2007). In public hospitals, the cost is RM 80,000 for the first surgery and RM 60,000 for battery replacement every 3-5 years (Kong, 2007).

Indeed, medication approach is commonly used to lessen the progression of tremor; however, the method is not effective and is plagued with side effects. Regarding the issues surrounding the medication method, the biomechanics method could be a possible way to “fill the gap” between these extremes in treatment. This non-invasive method mainly targets human hand by sensing the tremor behaviour and cancelling it using an actuator system. This thesis will only focus on control of hand tremors at postural conditions in the vertical direction because the tremor amplitude is the most significant for this axis (Ibanez, 2006).

1.3 Problem Statement

Debilitating conditions may perturb activities and tasks of daily living, especially eating, holding and writing. In order to abate the tremor, PD patients are normally treated with ingested medication or surgical technology. Although these can lessen the progression of tremor, to date, these methods have not proven to heal the tremor consistently (Archibald and Burn, 2008; Jiménez and Vingerhoets, 2012; Pahwa and Lyons, 2003). In addition, ingested medication can cause negative side effects (Jiménez & Vingerhoets, 2012), while surgical technology is very costly and hazardous (Lozano & Mahant, 2004).

In this study, the idea was to practice an engineering method by developing an external device either to wear or that is in close contact with the human body part that needs to be controlled. Previously, researchers have designed passive assistive devices where the limbs are assumed to be rigid. Some examples of the actuator components used are gyroscopic, vibration absorber and viscous beam (Hashemi *et al.*, 2004; Kalvert, 2004; Kotovsky and Rosen, 1998). The drawback of these passive assistive devices is that they not only suppress the tremor but at the same time resist all voluntary movement which the patient intends to make. For that reason, an active tremor suppression device is introduced with the objective of giving more comfort and better performance in attenuating tremor progression. The device is fitted when necessary to assist a patient in performing specific tasks for a certain period of time.

Prior to designing an active tremor control system, the test rig was developed to experimentally test the proposed designed controller in order to investigate the performance of the smart actuator with regard to attenuating hand tremors. The rig had to be capable of producing the vibration that emulates tremor behaviour when the actual signal (data from tremor patient) was injected into the shaker. In order to make the experimental design look more realistic, the hand model was developed using urethane rubber material which has a similar texture and feel to a real human hand. In this study, the controller to be implemented was the hybrid PI and Active Force Control and Iterative Learning (AFCAIL) controller. In simulation study, intelligent methods such as GA, PSO and DE were proposed to optimise the PI and EM parameters. In experimental work, the effectiveness of the LVCA in the suppression of hand tremors was assessed. There are some limitations of using LVCA, as the LVCA body must be held in order to produce force. It would appear that stabilisation of the hands could be one of the biggest benefits to those affected by pathological tremor.

1.4 Research Objectives

The objectives of this research are as follows:

a) To carry out comparative assessment of GA, PSO and DE methods in numerical simulation of an active force control scheme.
b) To develop mechatronic test rig to emulate PD tremor behaviour.
c) To develop, validate and analyse the performance of active force control tuning via an intelligent optimisation method on a test rig.
d) To develop and analyse the performance of online control strategies for the suppression of hand tremors using the intelligent active force control with iterative learning.

1.5 Scope of the Study

The scope of this research is as follows:

a) The actuator used in this study was of the linear voice coil type.

b) The type of controller implemented was Proportional-Integral (PI) and AFC with ILC.

c) The study was based on Parkinson's patients with a postural tremor condition.

d) The appropriate optimisation techniques, such as GA, PSO and DE, were applied to optimise the proposed controller gain.

e) System modelling of a tremor test rig used the least square estimation method.

f) A comparison study of the performance of tremor attenuation was based on the proposed optimisation technique

g) An experimental tremor test-rig that is capable of simulating actual tremors was developed. Also, the mechatronic design, data collection using PC-based equipment such as data acquisition interfacing with LabVIEW and application of appropriate sensors and actuators were used.

h) Experimental validation and evaluation was performed.

1.6 Research Contributions

The thesis makes several contributions to the hybrid control of tremors, which are reflected in several journal and conference papers arising from this work, as detailed in this section.

- The design, fabrication and test of test rig that capable to emulate actual hand tremor.
- Proposed AFC technique to suppress tremors of human hand through the implementation of optimisation techniques such as GA, PSO and DE through simulation study.

- Implementation of a DE-based tuning parameter PI-AFC controller with LVCA through experimental study.
- Implementation of PI and PI-AFCAIL controllers by means of LVCA in terms of level of vibration reduction and time response.
- Proposed a sensitivity analysis of the performance AFCAIL.

1.7 Organisation of the Thesis

A brief outline of the contents of the thesis is as follows:

Following the introduction, **Chapter 2** is devoted to the background of human hand tremor in terms of the types, medication approached and tremor behaviours. Past research about biomechanical devices which comprise active and passive devices is clearly addressed. Then, reviewsof the types of controller, actuator and sensor that are used is discussed. The chapter also introduces the work being done and applications of voice coil actuators, especially in vibration control.

Chapter 3 focuses more specifically on the simulation and dynamic model of the human hand. The chapter describes a mathematical model of 4-DOF that represents a human hand. For validation purposes, a parametric model of the tremor test rig which characterises the behaviour of hand tremors is described. A dynamic model of linear voice coil actuator is also derived.

Chapter 4 describes the development of the tremor test rig and other hardware components used to achieve the goal of tremor suppression through experimental tests. The experimental setup and calibration method for sensors and actuators is clearly addressed. In addition, the quantification of actual hand tremors is conducted to collect real tremor data that will be implemented or injected at the test rig in order to emulate tremors. Both actual and emulated tremor data are analysed.

Chapter 5 discusses the performance of proposed optimisation techniques in finding the optimal value of PI and AFC controller. Here, two models of hand tremor, the 4-

DOF model and the parametric model, are evaluated through a simulation study. Then, the optimal controller parameters for the parametric model will be implemented in a test rig and both simulation and experimental results will be validated. The performances of the control strategies are assessed in terms of the level of vibration reduction.

Chapter 6 extends the development of hybrid active force control with iterative learning (AFCAIL) in suppressing tremors on a test rig. The iterative learning scheme considered is the P-type. A sensitivity analysis is performed to demonstrate the robustness of the proposed controller in a real-time control environment. The system performance with the controllers is presented and analysed.

Chapter 7 sums up the dissertation with notable remarks and achievements. Possible future research directions are also outlined.

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