UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Engineering

DESIGN AND ANALYSIS ON THE ROBUST CONTROL OF A *X-Y* BALLSCREW MECHANISM

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A thesis submitted
In fulfillment of the requirements for the degree of Master of Science
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DECLARATION

I declare that this thesis entitled "Design and analysis on the robust control of a *X*-*Y* ballscrew mechanism" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	…………………………
Name	:	HEE WAI KEAT
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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechatronic Engineering.

Signature	:	……………………………
Name	:	DR. CHONG SHIN HORNG
Date	:	……………………………

DEDICATION

To my beloved father, mother and brother.

ABSTRACT

This thesis presents the design and analysis on the robust control of a *X*-*Y* ballscrew mechanism. In this research, a practical and robust controller for positioning control is discussed. The Continuous Motion Nominal Characteristic Trajectory Following (CM NCTF) controller is investigated in this research for tracking motion of an AC driven *X*-*Y* ballscrew mechanism. The CM NCTF controller has a simple control structure and straightforward design procedure that does not require an exact model parameter of a plant. In order to enhance the accuracy of the control system, a suitable input signal is designed to make sure the *X*-*Y* ballscrew mechanism attenuate smoothly in the deceleration motion. The CM NCTF controller consists of a Nominal Characteristic Trajectory (NCT) and a Proportional and Integral (PI) compensator. The NCT is constructed using the open-loop experimental responses while the PI compensator is designed based on a practical stability limit obtained experimentally. The CM NCTF controller has been evaluated in tracking motion performance. In order to examine the adaptability of the controller to the change of the input, experiments with various inputs is carried out. Besides that, the robustness of the controller is validated through the change of the load of the system. In order to examine the usefulness of the CM NCTF controller, a PI-D controller that has a similar control structure is designed and compared. The tracking performance of the CM NCTF controller is evaluated in maximum peak error E_{max}, percentage of error $E_{percent}$, and root mean square of error E_{rms}. E_{max} is the difference between the output peak and the reference input, and $E_{percent}$ is the percentage of the peak error with respect to the reference input. The experimental results proved that the CM NCTF controller has demonstrated better positioning response than the conventional NCTF controller and the PI-D controller by showing a two times smaller motion error. The robustness of the CM NCTF controller is clarified using *X*-axis, which has heavier load than the *Y*-axis. The experimental results have again proved that the CM NCTF controller demonstrates better tracking performance than the conventional NCTF controller and the PI-D controller in *X*-axis. As a conclusion, the CM NCTF controller has better positioning performance as compared to the conventional NCTF controller and PI-D controller. In future, the contour motion for *X*-axis and *Y*-axis will be done to evaluate accuracy of the controller. Besides that, the robustness performance in term of change of disturbance force will be considered.

ABSTRAK

Tesis ini membincangkan rekabentuk dan analisis pengawal berciri mantap pada mekanisma skru bebola X-Y. Dalam penyelidikan ini, satu pengawal yang praktikal dan teguh untuk kawalan gerakan mekanisima telah dibincangkan. Pengawal gerakan berterusan mengikut ciri nominal trajektori (CM NCTF) disiasat dalam penyelidikan ini untuk gerakan pengesanan bagi mekanisma skru bebola X-Y yang digerakkan oleh motor AC. Pengawal CM NCTF mempunyai struktur kawalan yang mudah dan tatacara rekabentuk yang senang untuk difaham, di mana pengawal ini tidak perlu mengetahui parameter model yang tepat. Untuk mengetahui kejituan sistem kawalan, masukan yang sesuai untuk mekanisme skru bebola X-Y telah direka. Tujuan masukan ini direka adalah untuk memastikan mekanisma tidak menurun secara mendadak. Pengawal CM NCTF terdiri daripada ciri nominal trajektori (NCT) dan pemampas berkadaran serta kamiran (PI). NCT dibina menggunakan jawapan eksperimen yang diperolehi daripada sistem gelung terbuka manakala pemampas PI direka berdasarkan had kestabilan praktikal yang diperolehi secara eksperimen. Pengawal CM NCTF telah dinilai dengan menjejaki gerakan yang diusul. Bagi memeriksa kebolehsuaian pengawal dengan perubahan masukan, eksperimen dengan pelbagai jenis masukan telah dijalankan. Selain itu, keteguhan pengawal telah disahkan melalui perubahan beban sistem (paksi-Y dan paksi-X). Bagi memeriksa keberkesanan pengawal CM NCTF, pengawal PI-D yang mempunyai struktur kawalan yang serupa telah direka bentuk dan dibandingkan. Ralat puncak maksimum E_{max}, peratusan ralat $E_{percent}$, and punca kuasa dua min ralat E_{rms} telah digunakan untuk menyesahkan penyesuaian pengawal CM NCTF. E_{max} ialah hasil pembezaan keluaran puncak dengan masukan rujukan, dan $E_{percent}$ ialah peratusan ralat puncak dengan masukan rujukan. Hasil percubaan eksperimen telah membuktikan bahawa pengawal CM NCTF menunjukkan kawalan gerakan yang dua kali lebih baik daripada pengawal konvensional NCTF dan pengawal PI-D dengan menunjukkan ralat usul lebih kecil. Keteguhan pengawal CM NCTF telah diuji pada paksi-X yang lebih berat berbanding dengan paksi-Y. Daripada keputusan eksperimen didapati bahawa pengawal CM NCTF lebih teguh berbanding dengan pengawal konvensional NCTF dan pengawal PI-D. Kesimpulannya, pengawal CM NCTF mempunyai prestasi yang lebih baik berbanding dengan konvensional NCTF dan pengawal PI-D. Pada masa akan datang, gerakan kontur untuk paksi-X dan paksi-Y akan dilakukan untuk menilai ketepatan pengawal. Selain itu, pretasi keteguhan dari segi perubahan daya gangguan akan dipertimbangkan.

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LIST OF ABBREVIATIONS

ABBREVIATION	DETAILS
ABSMC	Adaptive back-stepping sliding mode controller
AC	Analogue current
ADC	Analogue to digital converter
AR-CM NCTF	Acceleration Reference-CM NCTF
ASMC	Adaptive sliding mode controller
BSMC	Backstepping sliding mode controller
CAN	Controller area network
CFRNF	Chebyshev functional recurrent neuro-fuzzy network
CM NCTF	Continuous Motion Nominal Characteristic Trajectory Following
CNC	Computer numerical control
D/A	Digital to analogue
DAC	Digital to analogue converter
DC	Direct current
DOB	Disturbance observer
DOD	Drop on demand
DOF	Degree of freedom
DOFVSC	Disturbance observer based-filtered variable structure controller
EMECS	Electro mechanical engineering control system
GPIO	General-purpose input/output

I/O	Input/output
LAN	Local area network
MATLAB	Matrix laboratory
MFNCT	Modified fast NCT
MNCT	Modified NCT
NCT	Nominal Characteristic Trajectory
NCTF	Nominal Characteristic Trajectory Following
P	Proportional
P/PI	Proportional/Proportional Integral
PC	Personal computer
PD	Proportional Derivative
PDDO	Proportional Derivative with Disturbance Observer
PI	Proportional Integral
PID	Proportional Integral Derivative
PI-D	Proportional Integral – Derivative
PTP	Point-to-point
SMC	Sliding mode control
SRNF	Smooth robust nonlinear feedback
VCM	Voice coil motor

LIST OF SYMBOLS

SYMBOL		DETAILS
$X-Y$	-	*X*-axis and *Y*-axis
τ	-	Torque
ℓ	-	Position
d	-	Disturbance
π	-	Pi (3.14159265359)
f_b	-	Gain crossover frequency
f_{BW}	-	Bandwidth or cut-off frequency
x	-	Displacement
$\dot{x}$	-	Velocity
x_r	-	Reference input
M	-	Mass
C_d	-	Damping coefficient
K_m	-	Motor force constant
u	-	Input signal
t_f	-	Stopping time
K	-	Constant
x_f	-	Final displacement
t_{start}	-	Step up time

t_a	-	Step period
t_b	-	Exponential period
e^{-at}	-	Exponential ratio
K_p	-	Proportional gain
K_i	-	Integral gain
ξ	-	Zeta (Damping ratio)
ω_n	-	Natural frequency
K_{pu}	-	Ultimate proportional gain
$E_{\max}$	-	Maximum peak error
$E_{percent}$	-	Percentage of maximum peak error with reference input
E_{rms}	-	Root mean square error
emf	-	Electromagnetic force
K_a	-	Amplifier gain
K_t	-	Motor torque constant
J	-	Inertia
B	-	Damping coefficient
K_b	-	Back *emf* constant
$(\dot{x}_r - \dot{x})$ or $\dot{e}$	-	Error rate
β	-	Inclination near origin
m	-	Gradient

UNIT		**DETAILS**
rad	-	Radian
mm	-	Millimetre
rev	-	Revolution
µm	-	Micrometre
V	-	Voltage
Hz	-	Hertz
A	-	Ampere
kg	-	Kilogram
N	-	Newton
%	-	Percentage
s	-	Second
dB	-	Decibel

LIST OF PUBLICATIONS

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CHAPTER 1

INTRODUCTION

1.1 Background

Positioning mechanism that widely used in manufacturing systems is always aiming high-precision positioning. Thus, positioning control system in industries has high demands on high-precision positioning in order to maintain the quality of the product. Most of the industrial mechanisms usually operate at high speed for high productivity. The demand of the controller, which is practical, easy to design, simple control structure, fast response, small or no overshoot, and high robustness performance is increasing from time to time. In reality, the engineers in industry prefer to use equipment which is able to produce good performance in order to maintain the high speed production. Hence, practical controller, which has a simple control structure, easy to design, high adaptivity, and robust to the change of plant parameters is always a solution that needed in industry.

The controller plays an important role in a system, because one of the goals of the controller is to achieve stability and robustness in the system. Besides that, the controller also is functioned to make sure the system is able to obtain the desired output which set by the user. Since each mechanism will require a controller to make sure the process is smooth, therefore the structure of the controller should be simple and easy to understand by any engineer. As the controller has a simple structure and simple design procedure, the employer will not require to spend more budget to hire the supplier as the mechanism changes its function.

Up to now many types of controllers have been proposed and evaluated for positioning systems; for example, proportional-integral-derivative (PID) controller. PID controller is highly recommended and widely used by industrial field due to structural simplicity. With its three-term functionality, it is easy to be tuned and achieved effectiveness. However, PID controller has met the limitation when a higher positioning performance and robust systems are required. In order to achieve the better requirements, different types of controller have been proposed such as advance PID controller, disturbance observer (DOB), sliding mode control (SMC), and adaptive fuzzy controller. However, these advanced controllers require the exact model of the plant; which is time consuming to identify each parameter. It is difficult for engineer who is unfamiliar with advanced control to adjust and handle the control parameters in industrial. Besides that, these more complex advanced intelligent control methods such as disturbance observer based-filtered variable structure controller, friction compensation, adaptive back-stepping sliding mode controller, fuzzy-logic with deadzone compensator, and Chebyshev functional recurrent neuro-fuzzy network are less favourably under practical conditions and require high knowledge of control theory.

Nominal Characteristic Trajectory Following (NCTF) controller is proposed to overcome the problems stated above (Wahyudi et al., 2001). NCTF controller highlights the easy design procedure and simple structure. Besides that, exact model parameters are not required when designing NCTF controller. Therefore, less knowledge of control theory is required when designing NCTF controller.

In this research, *X*-*Y* ballscrew mechanism is used as an actuator to validate the effectiveness of the designed controller. The *X*-*Y* ballscrew mechanism is an automated machine which is able to provide a horizontal motion along *X*-axis and *Y*-axis. This application is commonly used in the fields like general machinery, pharmaceutical, manufacturing and semiconductor. In manufacturing field, *X*-*Y* ballscrew mechanism is