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FUZZY-BASED NCTF CONTROL OF POINT-TO-POINT (PTP) LINEAR POSITIONING SYSTEM

BY

PURTOJO BIN SOEJARNO

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requirements for the degree of Master of Science
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Kulliyyah of Engineering
International Islamic University
Malaysia

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ABSTRACT

Nominal characteristic trajectory following (NCTF) controller, which consists of a nominal characteristic trajectory (NCT) and a compensator, is a practical controller since its design is only based on a very simple open-loop experiment. The purpose of the compensator in NCTF controller is to make an object motion follows the NCT and to end the motion at the origin. Its simplicity even more increased by the introduction of fuzzy compensator compared to trial and error original PI compensator. However, some problems with the existed fuzzy compensator still occurred, such as it has redundant structure, some uncertain parameters definition and only effective for a small displacement. In this study, practical fuzzy compensator for an NCTF controller is proposed to overcome existing problems. The proposed fuzzy compensator is practical since its all design parameters are based on NCT information and hardware specifications used; which are sensor resolution and actuator rated input; only. Trial and error or uncertain parameters value are completely eliminated. By using a linear positioning system, control performance of the proposed compensator and its robustness are examined. The results show that the proposed compensator is effective for the entire displacement range and able to force object motion as fast as determined by the NCT. Proposed compensator has consistently outperformed the PI and existed fuzzy compensators. The robustness is evaluated through experiments with payload to represent inertia variation of the system. The results show consistent performances are achieved. Design process, performance and robustness evaluation show that the proposed practical fuzzy compensator of NCTF controller is effective for positioning systems.

ملخص البحث

يتكون متتبع مسار الخصائص الاسمية NCTF من مسار الخصائص الاسمية NCT و معدل , و هو عبارة عن مسيطر عملي يعتمد تصميمه على تجربة الدائرة المفتوحة البسيطة. الغرض من المعدل في مسيطر ال NCTF هو جعل حركة جسم معين تتبع NCT و تنتهي في نقطة المركز.و تزداد سهولته باستخدام المعدل الغامض fuzzy بدلا من طريقة التجربة و الخطأ كما في حالة معدل ال PI . رغم ذلك ما زالت هناك بعض المشاكل الحاصلة في حالة استخدام المعدل الغامض العادي مثل التركيب العشوائي و عدم وثوقية بعض المعاملات الا في حالات ازاحية بسيطة. لذلك تم في هذه الدراسة اقتراح المعدل الغامض لمسيطر ال NCTF للتغلب على المشاكل الحالية, و يمتاز بعمليته من حيث ان كل معاملات المسيطر تعتمد على معلومات ال NCT و مواصفات الاجهزة المستخدمة واهمها حساسية جهاز القياس و مدى عمل المشغل. و لقد تم التخلص من حالة التجربة و الخطأ و عدم وثوقية المعاملات بشكل نهائي. كما تم اختبار المسيطر المقترح بواسطة جهاز حركة خطي . و اثبتت النتائج المختبرية فاعلية الطريقة المقترحة على طول مدى المسار و بالسرعة المحسوبة في ال NCT و كذلك تغلبها على اداء المسيطر PI و المسيطر الغامض fuzzy العادي. و لقد اضيف حمل خارجي للجهاز لفحص صلادة اداء المسيطر المقترح و ثبوتيته.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechatronics Engineering).

…………………………...............
Rini Akmeliawati
Supervisor

…………………………...............
Wahyudi Martono
Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechatronics Engineering).

…………………………………....
Muhammad Mahbubur Rashid
Internal Examiner

…………………………………....
Mohd Fua'ad Bin Hj. Rahmat
External Examiner

This dissertation was submitted to the Department of Mechatronics Engineering and is accepted as a partial fulfilment of the requirements for the degree of Master of Science (Mechatronics Engineering).

……..……………………………..
Wahyudi Martono
Head, Department of Mechatronics

This dissertation was submitted to the Kulliyyah of Engineering and is accepted as a partial fulfilment of the requirements for degree of Master of Science (Mechatronics Engineering).

……………………………………
Amir Akramin Shafie
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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To my beloved family

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Alternating Current
CNC	Computer Numerical Control
COA	Center of Area
CP	Continuous Path
DC	Direct Current
DNPF	Discontinuous Non-linear Proportional Feedback
Eq., Eqs.	Equation, Equations
Fig.	Figure
NB	Negative Big
NS	Negative Small
NCT	Nominal Characteristic Trajectory
NCTF	Nominal Characteristic Trajectory Following
PB	Positive Big
PD	Proportional and Derivative
PI	Proportional and Integral
PID	Proportional, Integral and Derivative
PS	Positive Small
PTP	Point-to-Point
SRNF	Smooth Robust Non-linear Feedback
Z	Zero

LIST OF SYMBOLS

A	Maximum error in the deceleration region of NCT
A_r	Deceleration range
a_{sres}	Sensor resolution
α	Simplified object parameter constant
B	Total viscous damping
B_l	Load viscous damping
B_m	Motor viscous damping
B_r	Rotating parts viscous damping
B_s	Sliding components viscous damping
$\frac{d}{dt}$	Derivative with respect to time
e	Error
$\dot{e}$	Error-rate
F	Force
$G(s)$	Closed-loop transfer function
$G_c(s)$	Controller transfer function in Laplace domain
h	Maximum error-rate (mm/s, rad/s)
h_{sres}	Error-rate at sensor resolution
$i(t)$	Electric current
$I(s)$	Electric current in Laplace domain
J	Total inertia
J_l	Load inertia
J_m	Motor inertia
J_r	Inertia of rotating part
K	Simplified object parameter constant
K_b	Back emf constant
K_f	Fuzzy gain
K_i	Integral gain
K_p	Proportional gain
K_{p_u}	Ultimate proportional gain
L	Motor inductance
M	Mass
m	NCT slope at about origin
μ_u	Degree of membership u
μ_{u_i}	Degree of membership u_i
μ_{u_p}	Degree of membership u_p
ω_n	Natural frequency

$\omega_m(t)$ Motor angular speed
$\Omega_m(s)$ Motor angular speed in Laplace domain
P Ballscrew pitch
R Resistance
s Laplace operator
ς Damping ratio
ς_{prac} Practical damping ratio
T Sampling period
$\dot{\theta}$ Velocity
$\dot{\theta}_m$ rotating angular velocity
$\dot{\theta}_r$ Derivative of input reference
τ Torque
$\tau_m(t)$ Motor torque
$\tau_l(t)$ Load torque
$\mathrm{T}_m(s)$ Motor torque in Laplace domain
u Control signal
$U(s)$ Control signal in Laplace domain
u_i Integration of u_p
$u_{i\max}$ Maximum of u_i
u_{isres} Integration of u_p at a_{sres}
u_p Difference between actual velocity to NCT error-rate
u_r Actuator input
$u_{r\max}$ Maximum actuator input rated (V)
$u_{r\min}$ Minimum actuator input rated (V)
$v(t)$ Motor input voltage
$v_{emf}(t)$ Back emf voltage in Laplace domain
$V(s)$ Motor input voltage in Laplace domain
$\dot{x}$ Linear velocity
x_r Input reference
$\dot{x}_r$ Derivative of linear input reference
$X(s)$ Object displacement in Laplace domain
$X_r(s)$ Displacement reference in Laplace domain
$\vee$ Maximum operator
$\wedge$ Minimum operator

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Positioning systems that can achieve high accuracy are essential and play important roles in industrial equipments such as machine tools, semiconductor manufacturing systems and robot systems. Implementation of motion control for positioning system can be classified into two types. The first type is continuous path (CP) control system and the second one is point-to-point (PTP) positioning system. PTP positioning systems are used to move an object from one point to another point either in angular or linear direction. The fields of precision positioning recognize that precision positioning systems are expected to have the accuracy better than 10μm (Sato, 2006).

PTP positioning systems are widely used in industries. Many tasks can be considered as PTP operations such as spot-welding operation, pick-and-place and computer numerical control (CNC) machines. In spot-welding robot, PTP positioning is used to locate the manipulator from one spot location to another. In CNC machines, PTP positioning is used to accurately locate the spindle at specific locations to perform operations, such as drilling, reaming, boring, and punching (Krar, 1999).

PTP positioning system requires high accuracy, fast response with no or small overshoot and robust to parameter variations. High accuracy at endpoint often must be achieved in shortest time regardless the motion path. This means that the most important requirements in PTP positioning systems are the final accuracy (stedy state error) and transition time (rise time). The transient path is considered as the second important (Wahyudi, 2002). In its applications, positioning system may experience parameter variations due to payload. In this case, the system performance is expected to be the same or as close as its performance when the system is in normal condition. Thus, robustness is also important requirement in order to guarantee the system performance consistency.

In order to satisfy the requirements, a good controller is required. Many types of controllers have been proposed and evaluated for positioning systems. For example, the model-based type controller such as controllers with disturbance observer (Kempf and Kobayashi, 1999), time-optimal controller (Park and Won, 1991) and sliding-mode controllers (Fujimoto and Kawamura, 1995) have been proposed. Mostly, controllers will give good positioning performance with prior knowledge experts on motion control systems design the controller. Moreover, sufficiently good approximate model and values of its parameters are also required by the experts to design the controller. However, deriving a sufficiently good approximate model and performing parameters identification are often complicated, troublesome and time consuming tasks. In general, advanced controllers tend to be complicated and require deep knowledge concerning with controller theory and design.

In practical applications, engineers who are not experts in control systems theory often need to design controllers. Hence, controller design that is relatively easy with simpler of controller structure is very important in practical applications. In order to overcome these problems, nominal characteristic trajectory following (NCTF) controller had been proposed as a practical controller for PTP positioning systems (Wahyudi, 2002). The controller design procedure is simple since it is only based on a simple open-loop experiment. In addition, a simplified model of the object derived from the open-loop experiment is adequate. Thus, this controller is easy to design, understand and adjust.

The NCTF controller consists of a nominal characteristic trajectory (NCT) and a compensator. Initially, NCTF control system had a proportional and integral (PI) compensator which was designed without any systematic procedure in obtaining the best PI compensator parameters. A trial and error approach in designing the PI compensator can lead to a cumbersome and time consuming process. Introduction of a fuzzy compensator to replace the PI compensator is intended to increase the simplicity of NCTF controller design process (Wahyudi et al., 2007a). Since all the compensator parameters of the NCTF controller are based on the NCT information, the introduction of the fuzzy compensator adopted this approach. By relating the NCT information to the fuzzy compensator parameters design, the complexity can be reduced. Thus, trial and error process to determine compensator parameters can be eliminated.

1.2 PROBLEM STATEMENT

The simulation results using a dynamic model of rotary positioning system had shown the effectiveness of the NCTF controller with fuzzy compensator. It was also robust to parameter variations (Wahyudi et al., 2007b). However, the investigation was conducted to a small input reference only. The small input refers to an input within the deceleration range of NCT. In order to satisfy requirement of short transient time, maximum velocity of the object motion should be achieved. Its performance should also robust to parameter variations. Thus, the NCTF controller with fuzzy compensator, which is effective for the entire range of actuator capability and robust to parameter variations, is needed.

1.3 RESEARCH OBJECTIVES

The objectives can be described as follows,

i. To propose a new fuzzy compensator structure in order to eliminate compensator structure redundancy of the existing NCTF controller with fuzzy compensator.

ii. To propose a systematic and efficient method on selecting fuzzy compensator parameters based on existing information to eliminate trial and error process or uncertain parameters definition.

iii. To improve controller performance and its robustness due to parameter variations for the entire range from a small to a large displacement.

1.4 RESEARCH METHODOLOGY

The following works conducted in order to achieve the objectives of this research:

i. The literature survey was conducted by with exploring the PTP positioning control using NCTF control system. Its fundamental principles, developments and problems are analyses.

ii. Experimental system setup was for real-time implementation of the proposed fuzzy-based NCTF controller. A linear positioning system was used as the object to be controlled.

iii. Design of the fuzzy-based NCTF controller. The proposed design procedure relates the available information to be used for controller design in a simple and straightforward way.

iv. Experiments were conducted as part of design procedure and performance evaluation. The practical design process evaluated since the NCTF controller is designed based on a simple open-loop experiment.

v. Evaluation of the proposed controller performance. The performance compared with other controllers and the robustness examined through experiments.

1.5 SCOPE OF THESIS

The scope of this research covers fuzzy-based NCTF controller for PTP linear positioning system. This study is conducted in order to improve the performance and practical design aspects of the NCTF controller with fuzzy compensator. The study is directed to obtain the best controller design for the entire range of the actuator capability. The performances to a small and large input reference are expected consistent. Moreover, higher practical aspect of the controller design process is expected. All of the design parameters should only be taken from NCT information and hardware specifications. Improvements of its practical design aspect and performance contribute to the development of intelligent-system-based NCTF controller.

In this study, the object to be controlled is a linear positioning system instead of dynamic model of rotary positioning system used in the past researches. By using this system, the entire range of the system can be clearly determined. The design process using the linear positioning system is shown and the controller performance is evaluated. The controller performed PTP positioning operations to evaluate the controller performances. Robustness of the controller is examined through experiment. An additional load is introduced to represent parameter variations.

1.6 THESIS OUTLINE

This thesis can be summarized as follows,

Chapter 1: Introduction. This opening chapter describes the background and problem statement of this study, objectives to be achieved and methodology of the research, and scope and outline of this thesis.

Chapter 2: Literatures review. This chapter discusses the researches and developments of the NCTF control system. The NCTF controller with PI compensator, referred as classical approach, is one of the two main approaches of the researches. The intelligent-system-based refers to the second approach. The discussion covers both approaches applied to the PTP positioning system. In this chapter, the basic concept of NCTF control theory is also reviewed. Firstly, the basic concept of NCTF control is described. Then, its design is explained. The design covers the NCT determination and its compensator design. Detail discussion of the PI compensator design is presented while the fuzzy compensator design is presented in Chapter 4. In this chapter, simplified object parameters are also explained.

Chapter 3: Experimental Setup. This chapter explains the experimental setup of this study. A linear positioning system along with a real-time implementation system is used. Description of its setup and model of the system are described.

Chapter 4: Practical fuzzy compensator. The proposed practical fuzzy compensator for NCTF controller is then discussed in this chapter. Deep discussion of its structure, membership function design, inference mechanism and rule base are explained. The discussion emphasizes the relation of the NCT information and the hardware specifications as sufficient information to design the compensator.

Chapter 5: Results. Chapter five discusses the evaluation of the proposed compensator with linear positioning system. The controller design process using the linear positioning system is presented. Robustness evaluation is discussed along with performance evaluation of the compensator and the comparison with other design.

Chapter 6: Conclusions. In this chapter, results obtained in the previous chapters are summarized and discussed. Themes for future studies are also explained.

CHAPTER TWO

LITERATURES REVIEW

2.1 INTRODUCTION

Precision positioning systems are fundamental components in industrial machines. Its performances depend on the characteristics of mechanisms and the controllers which has the role to overcome the mechanical limitations and to utilize their characteristics for high positioning performance. Machine elements used in precision positioning systems often have the characteristics that deteriorate their positioning performance, for example is friction. Thus, higher desired system performance and lower characteristics of the mechanism increase the important of the controller (Sato, 2006).

The control design process of the NCTF control system is practical for mechanisms with friction. Since it was proposed, the research on this topic can be divided into two approaches. The first one is the NCTF controller with PI compensator, referred as classical approach while the second one is the NCTF controller with the intelligent-system-based compensator. In the classical approach, practical methods are developed in order to obtain the simplest way in determining the PI compensator parameters. Either theoretical or practical methods have been investigated. In the intelligent system based NCTF controller, the practical method is developed for a fuzzy-based system particularly. The introduction of fuzzy compensator is intended to increase the simplicity of NCTF controller design process (Wahyudi, 2007a).

As discussed previously in Chapter 1, NCTF controller was initially proposed as a practical control for PTP positioning system. In addition to its performance, its