# UNIVERSITI TEKNIKAL MALAYSIA MELAKA

## PID AND NONLINEAR PID CONTROLLER FOR TRACKING PERFORMANCE OF XY TABLE BALL SCREW DRIVE SYSTEM

This report submitted in accordance with requirement of the Universiti Teknikal Malaysia Melaka (UTeM) for the Bachelor Degree of Manufacturing Engineering ( Robotics and Automation) (Hons.)

by

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# UNIVERSITI TEKNIKAL MALAYSIA MELAKA

**BORANG PENGESAHAN STATUS LAPORAN PROJEK SARJANA MUDA**

TAJUK: **PID and Nonlinear PID for Tracking Performance of XY Table Ball Screw Drive System**

SESI PENGAJIAN: **2014/15 Semester2**

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# APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of UTeM as a partial fulfillment of the requirements for the degree of Bachelor of Manufacturing Engineering (Robotics and Automation) (Hons.). The member of the supervisory is as follow:

………………………………
(Dr. Ir. Lokman bin Abdullah)

# DEDICATION

Special dedication to my lovely parents and sibling,
my friends and all faculty members

For your encouragement, support, care and believe in me
during my study in UTeM

# ABSTRACT

The demand for tracking performance and precision arouse the development of machine tool technology and the approach on how to design the control structure. One of the factor that contribute to the inaccuracy of a machine tool is the tracking performance of its drive system. The main objective of this research project is to design PID and NPID controller that is able to control the tracking performance of the system which is XY table ball screw drive system. XY table ball screw drive system is a basic structure of Computer Numerical Control (CNC) machine. This project will include the research regarding system design and analysis performance of PID and Nonlinear PID in term of Maximum Tracking Error and Root Mean Square Error (RMSE). Data collection for both controllers are observed numerically and experimentally using MATLAB/Simulink software and XY table ball screw drive system. This research project also proposes an approach to compensate multiple frequency components at y-axis of XY table. Moreover, various types of graphs are illustrated to show the comparison between simulation and experimental work of the controller. The results show than NPID controller has better tracking performance compared to PID controller. Based on Root Mean Square Error (RMSE), NPID controller shows better performance that PID controller with the percentage reduction are 0.3145 % for frequency of 0.3 Hz while for 0.5 Hz is 0.3788 %. However, further studied and improvement are desired in order to improve the tracking performance of the controller. This improvement includes addition of controller to compensate the tracking error from various different cutting force disturbances. In addition, it is recommended that the study on the design of the controller is carried out the actual cutting experiment in order to find the relationship about the cutting spindle speed and the performance of the controller.

# ABSTRAK

Permintaan untuk prestasi pengesanan dan ketepatan mencetuskan perkembangan teknologi mesin alat dan pendekatan bagaimana untuk merekabentuk struktur kawalan. Salah satu faktor yang menyumbang kepada ketidaktepatan alat mesin adalah prestasi pengesanan sistem pemanduannya. Objektif utama projek penyelidikan ini adalah untuk merekabentuk PID dan NPID yang mampu mengawal prestasi pengesanan mesin XY. Mesin XY adalah struktur asas mesin CNC. Projek ini akan merangkumi kajian mengenai reka bentuk sistem dan analisis sistem PID dan NPID dari segi "Maximum Tracking Error" dan "Root Mean Square Error (RMSE)". Pengumpulan data untuk kedua-dua sistem kawalan dinilai secara berangka dan uji kaji menggunakan perisian MATLAB/Simulink dan mesin XY. Projek penyelidikan ini juga mencadangkan satu pendekatan untuk mengatasi sesuatu komponen frekuensi yang berbeza pada paksi y bagi mesin XY. Selain itu, pelbagai jenis graf digambarkan untuk menunjukkan perbandingan antara simulasi dan ujikaji sistem kawalan. Keputusan menunjukkan bahawa sistem kawalan NPID mempunyai prestasi pengesanan yang lebih baik berbanding sistem kawalan PID. Berdasarkan aspek "Root Mean Square Error (RMSE)", sistem kawalan NPID menunjukkan prestasi yang lebih baik dari sistem kawalan PID dengan pengurangan peratusan sebanyak 0.3145% untuk frekuensi 0.3 Hz manakala bagi 0.5 Hz adalah 0.3788%. Walau bagaimanapun, kajian lanjut dan peningkatan adalah dikehendaki untuk meningkatkan prestasi pengesanan sistem kawalan. Peningkatan ini merangkumi penambahan sistem kawalan untuk mempertingkatkan lagi kebolehan sistem kawalan agar ia mampu bertahan pada pelbagai gangguan daya pemotongan. Di samping itu, ia adalah disyorkan bahawa kajian mengenai reka bentuk sistem kawalan dijalankan menggunakan eksperimen pemotongan sebenar untuk mengetahui hubungan tentang kelajuan pemotongan dengan prestasi sistem kawalan.

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# LIST OF ABBREVIATIONS, SYMBOLS & NOMENCLATURE

| | | |
|---|---|---|
| CNC | - | Computer numerical control |
| DAC | - | Digital to Analog |
| DDL | - | Direct Drive Linear |
| DSP | - | Digital signal processor |
| FRF | - | Frequency response function |
| I/O | - | Input/output |
| LTI | - | Linear time invariant |
| MMI | - | Man machine interface |
| NLLS | - | Nonlinear least square |
| NPID | - | Nonlinear Proportional-Integral-Derivative |
| PI | - | Proportional- Integral |
| PD | - | Proportional-Derivative |
| PID | - | Proportional-Integral-Derivative |
| RMSE | - | Root Mean Square Error |
| SISO | - | Single input single output |
| $d(t)$ | - | Disturbance |
| $e(t)$ | - | Error signal |
| $e_p(t)$ | - | Position tracking error |
| $e_{max}$ | - | Maximum value of error |
| $Fc$ | - | Cutting force |
| $Ft$ | - | Thrust force |
| $Fs$ | - | Cutting speed |
| $fe$ | - | Scaled error |
| $G(s)$ | - | System |
| $KO$ | - | Rate of variation for nonlinear gain |
| $K_p$ | - | Proportional gain |
| $K_i$ | - | Integral gain |
| $K_d$ | - | Derivative gain |

| | | |
|---|---|---|
| $K_e$ | - | Nonlinear Gain |
| $N(t)$ | - | Noise |
| $R$ | - | Resultant force |
| $r(t)$ | - | Reference input signal |
| $T_d$ | - | Time delay |
| $U(t)$ | - | Input signal |
| $Z_{ref}$ | - | Reference position |
| $Z$ | - | Output position |

# CHAPTER 1

# INTRODUCTION

This chapter give a brief explanation about this project, starting with the background of the project title PID and Nonlinear PID Controller for Tracking Performance of XY Table Ball Screw Drive System. Section 1.2 elaborates the detail of the problem statement of the project and followed by the objectives of the research in Section 1.3. Based on the problem statement and the objectives of the research, the scope of the limitation of this project can be identified in the Section 1.4. Finally, the organization of the project is discussed in the Section 1.5.

## 1.1 Background

Milling process is the common form of machining which can create a variety of features on a part by cutting away the unwanted material. The consistent needs for better tracking accuracy and precise positioning in machine tools have inspired the growth of machine tools technology through development of machine tools controller. The general knowledge and understanding on factors that contribute to machine accuracy are pivotal. One aspect that adds to the accuracy and precision of a machine tool is the tracking performance of the system which is XY table ball screw drive system. XY table ball screw drive system is basic structure of CNC machine. However, there exist several factors that could affect tracking performance of the drive system, such as the mechanical structure of the machine tools, mass variation and disturbance forces (Jamaludin, 2008). The presence of disturbance forces in the machine tools leads to inaccuracy in positioning and tracking performance. The disturbance forces can divide into two which are cutting forces and friction forces. Cutting forces is one of the disturbance forces that greatly affect the positioning and tracking performance of a machine tool. Thus, in order to get better tracking performance, the controller was designed and analyzed based on frequency domain approach.

Cutting force exists whenever there is cutting process involved in any machine tools application. In milling operation, the cutting force influence the nature of cutting force produced by the cutting parameters such as spindle speed, depth of cut and feed rate. Each cutting parameter variation will lead to different set of cutting force produced leading to different quality of finished work (Gokkaya, 2010). Excessive cutting force could also result in tool deflection and vibration. These if left unchecked will cause harm to operators and reduce surface finish quality (Nijiri et al., 2012). Thus, the quality of product can be improve if the appropriate design of machine controller applied on this XY table ball screw drive system.

## 1.2 Problem Statement

The tracking system plays an important role in high tracking performance of milling process. There are several demands for the machine tool such as better tracking performance, low cost, robustness and speed, high flexibility and better surface finish. However, presence of the disturbance force greatly leads to inaccuracy in tracking and positioning performances of XY table ball screw drive system. The cutting force is the one of the disturbance forces that may affect the positioning accuracy of machine tool system (Chiew et al., 2012). The classical PID controller is one of flexible controller that allowed benefits from the advanced of technology. It is combination of PI and PD controller which can improve both steady state error and transient response. An active and efficient controller needs to be designed into the system in order to achieve better tracking performance of the system.

## 1.3 Objectives

The objectives of this research are:

i. To design PID and NPID controller for tracking performance of XY table ball screw drive system.

ii. To validate the PID and NPID controller through simulation using MatLab/Simulink software and experimental work using real plant of Googoltech XY table ball screw driven system.

iii. To compare the performance of PID and NPID controller in term of Maximum Tracking Error and Root Mean Square Error (RMSE).

## 1.4 Scopes of Project

This project focuses on:

i. It is applied on the y-axis only.

ii. Simulation of the controller is validated by using MATLAB/Simulink software.

iii. The performance measures of the controllers are compared based on the maximum tracking error and root mean square error (RMSE).

iv. The frequencies used for simulation and experimental work are 0.3 Hz and 0.5 Hz.

## 1.5 Organization of Project

The research project are focused on how to designed controller to obtain better tracking performance of XY table ball screw drive system. The organization of the project are as: Chapter 1 describes the introduction of the PID and NPID controller for tracking performance of XY table ball screw drive system. It consists of background, problem statement, objectives and scope of the project. Chapter 2 discusses on literature review of the mechanical drive system in machine tools, disturbance forces in drive system and the controller design approach of PID and NPID controller. Next, Chapter 3 elaborates the methodology part of this research project. In general, it consists of overall flowchart on how to complete this project in step by step and planning of the research project. In addition, it discussed about the experimental setup for the project and system identification and system modelling of the system. Chapter 4 discusses the design and analysis of the each controller and general structure and configuration of the controller. It also discussed the numerical and experimental results of each design controller by compared based on the performance measured analysis. The results of the finding will be concluded in the Chapter 5 and recommendations for future work are also stated in this chapter.

# CHAPTER 2

## LITERATURE REVIEW

This chapter discussed on the information that can be identified to be relevant to the study. Section 2.1 elaborates the detail of the state of the art on motion control of machine tools. It covers an aspect of mechanical drive system of machine tools in Section 2.1.1 and the disturbance forces in drive system in Section 2.1.2. There are two types of disturbance force that greatly lead to positioning and tracking performance which are friction forces and cutting forces disturbance. In the Section 2.2, the two types of controller which are PID controller and NPID controller are discussed and elaborated in this section. Last but not least, in Section 2.3, the summary of the literature review is presented.

## 2.1 State of the Art on Motion Control in Machine Tool

Lately, mechanical drive system are progressing towards latest technology in order to meet the demands for high speed which is faster transient response and better precision in positioning of the system. However, this progression has created a new challenge task to the control community with respect to compensate the disturbance forces in order to achieve better tracking performance (Jamaludin, 2008). In general, this section elaborates on the chronological shift in mechanical drive system and a literature review on disturbance forces.

### 2.1.1 Mechanical Drive System

The advancement of the mechanical drives system technology has been improved from electromechanical drive systems to direct drive systems. In mechanical drive systems, it consists of four types of drive system namely direct drive linear system, rack and pinion drive system, ball screw drive system and piezoelectric drive system.

The first part of the drive system is Direct Drive Linear (DDL) motors. DDL motor is basically a rotary motor which delivers power to mechanical equipment without the utility for gears, belts or other intermediate mechanisms. In general, direct drive system comprises laminating stacks, coils and magnets while the type of motor associated with the direct drive is the special class of synchronous brushless servo motor as shown in Figure 2.3 (Anonymous, 2011). There are many benefit of the direct drive system such as it has a better positional accuracy compare to other types. So it will make them as preferred choice for precision of the system. The positioning error will reduce to small value when a motor uses gears, chains or belts; otherwise there more there are, the greater the errors (J.T. Barett, 2014). Moreover, this design delivers exceptional performance, very high velocities and accelerations, high positional accuracy, extremely high stiffness, higher throughput, compact mechanical assembly, silent operation, zero maintenance and smooth, and error-free motion by eliminating mechanical transmission components (Kollmorgen, 2011). Last but not least, the bandwidth of the system can be extended due to the absence of first natural frequency, which is usually associated with the ball screw drive system.

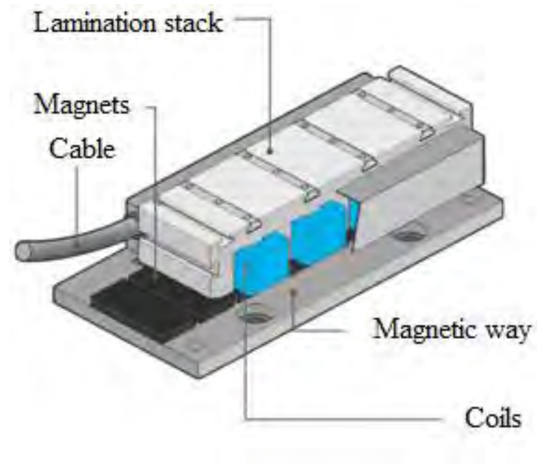


**Figure 2.1 :** Structure of iron-core linear drive system

Secondly is the rack and pinion drive system. Rack and pinions are one of simple mechanisms where a pair of gears come together to steer a vehicle by circular and linear motions (Jim Hagerty, n.d.). The spur gear is called pinion gear and straight or flat bar with teeth is known as rack gear. Pinion gear moves in rotary motion while rack gear moves in the linear motion. Its convert rotational motion to linear motion because the circular pinion engages teeth on the rack makes circular movements while the rack is moved side-to-side. When the rotational motion applied to the pinion, it will cause the rack to move to the side until up to the limit of its travel. Alternately, moving the rack will causes rotation in the pinion. According to Mike Anselmo, n.d., the rack and pinion is suitable for machine tools with long working path or unlimited length. It is because the rack and pinion drive system produced lower mass moment of inertia, higher natural frequency and efficiency, and high torque with low revolution in power transfer.

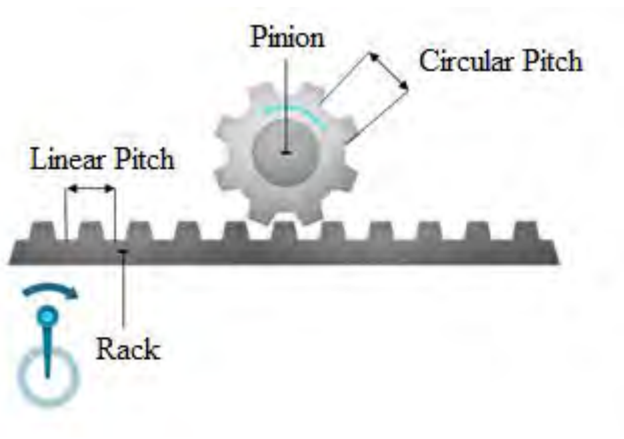


**Figure 2.2** : Rack and pinion drive system

Thirdly is the ball screw drive system. It is the mechanism that commonly used to provide linear motion in high speed machine tools. Besides that, the position accuracy and the achievable closed loop bandwidth is usually limited by the structural vibration modes of the mechanical components (Frey, 2011). In general, ball screw drive system is an assembly that converts rotary motion to linear motion (or vice versa). Basically, it consists of a ball screw and a ball nut packaged as an assembly with recirculating ball bearings. The interface between the ball screw and the nut is made by ball bearings which roll in matching ball forms. The recirculating parts are important because in case of ball bearing, the steel balls roll only in a circular grove so there are no way for steel balls to go out of it. However, the groove in the ball screw is helical so it easily for steel balls roll along the helical groove and may go out of the ball nut. Therefore, it is necessary to change their path after reached a certain point by guiding them back to their starting point known as formation of recirculating path (Anonymous, n.d.). The key benefit of the ball screw drives is has capability to adapt a range of machine sizes, feed rates and process forces. However, it has some drawback of the drive system (Pritschow, 1998). The lead screw component contributes unconstructively to the performance of the drive system in term of the tracking accuracy. It can be classified into two categories which are high helix lead and fine pitch lead. High helix lead is suitable for high speed operation because which this lead, the ball nut can travels a longer distance when the screw shaft makes one rotation. In term of the highly accurate positioning is more suitable because the ball nut only travels a shorter distance when the screw shaft makes one rotation (Anonymous, n.d.).