Precise Positioning Control Strategy of Machine Tools: A Review

Nur Amira Anang[1], Lokman Abdullah[1]*, Zamberi Jamaludin[1], Zain Retas[1], Chiew Tsung Heng[1], Syed Najib Syed Salim [2]

[1]Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia
[2]Faculty of Engineering Technology, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia.
lokman@utem.edu.my

***Abstract*— In this article, a precise positioning control strategy for the nonlinearity of machine tools is thoroughly reviewed. Precise positioning is crucial in machine tools industry where nonlinear phenomenon must be considered. Therefore, this paper aims to review various techniques used to enhance the precision of nonlinearity of machine tools. In the introduction, a significant review of machine tools is discussed based on deadzone phenomenon and high bandwidth. After that, linear control strategies are reviewed involving Proportional-Integral-Derivative (PID) and Cascade P/PI controller. This is followed by nonlinear control strategies, Nonlinear PID (NPID), Adaptive NPID (ANPID), Feedforward NPID (FNPID), Adaptive Robust Controller (ARC), Nominal Characteristics Trajectory Following (NCTF) controller and lastly, the fuzzy and neural network control is then reviewed. Finally, conclusions are presented according to the past researches conducted. Further studies regarding the topic can be improved by the implementation of several additional modules such as deadzone and feedforward compensators and disturbance observer that focus on both disturbance forces such as cutting force and friction force.**

***Index Terms*— Machine tools, precise positioning, nonlinear control.**

I. Introduction

The last few decades showed tremendous researches on the control strategy of machine tools, specifically in precise positioning. The machine tools include the linear or rotary motor drives that feed drives in a machine. According to Altintas [1], two most popular drives are ball screw and linear drive compared to rack and pinion drive where both promised high efficiency and precision in machine tools industry.

Since the machine tools has been widely introduced, several scholars reviewed the precision of machine tools [2]–[12] including several issues such as thermal issue [13] as well as investigation in vacuum environment [14] that has been covered for the past fifteen years.

One of the possible situations that might occur in a machine tool is a deadzone phenomenon. This phenomenon leads to the degradation of the overall performance of a system where precision and accuracy are crucial in the high precision application. With that, Ahmad et al. [15] came out with the idea of adaptive deadzone inverse controller as an improvement of the conventional deadzone compensator. One of the surprising advantages is the adaptation of the controller to combine with any advanced control methods. In 2015, He et al. [16] reported a new and convenient procedure to obtain zero error by combining the deadzone compensator with a nonlinear ARC.

However, Erkorkmaz and Kamalzadeh [17] proved that the control scheme for high bandwidth should not be neglected where they proposed a control strategy in solving high bandwidth positioning. A year later, they, found that there are several problems

that affect the motion accuracy [18]. The problems are due to structural vibrations, nonlinear friction, torque ripples, and external disturbances such as cutting force and friction force. With that, they came out with the comprehensive idea by combining the least square parameter estimation with Kalman filter. On the other hand, Erkorkmaz and Wong [19] suggested a significant identification technique for the virtual Computer Numerical Control (CNC) drives. The scholars designed several controllers such as cascade P/PI, PID, and adaptive Sliding Mode Controller (SMC) for simulation while experimental validation was done by two methods. First was by pole placement controller with Kalman filter and the second used zero phase error tracking controller.

On the basis of the comprehensive literature review, the adaptive nonlinear control strategy with several added modules such as feedforward compensator and disturbance observer of machine tools in catering disturbance forces such as cutting and friction force has rarely been reported. In the present paper, a review of control strategy for precise positioning of the machine tool in enhancing nonlinear phenomenon with more details is presented. To the best of authors' knowledge, there is no comprehensive literature on the subject.

II. Linear Control Strategies

PID controller is well-known and established controller in the world of control system. This is due to its simple design and straightforward approach [20]. The three component gains, KP, KI and KD are significant in tracking both transient and steady state response. The general equation of PID controller is as follows:

$$G(s) = K_P + K_I \frac{1}{s} + K_D s \quad (1)$$

Where K_P is the proportional gain, K_I the integral gain and K_D the derivative gain. Each of its components has its own functionality where proportional term provides the overall control actuation. The integral component helps in reducing steady state errors while the derivative gain improves the transient response [21], [22]. The tuning process involves the combination of these three terms in order to obtain optimum performance in a system. Recently, the improvement of PID controller has been tuned using genetic algorithm technique. According to Singh [23], genetic algorithm helps in fixing optimization problem by biological evolution. The value of the chromosome fitness was chosen to create the brand new population that consisted of the fittest members. The genetic algorithm is based on PID controller where consisted of three important steps. The steps are selection, crossover, and mutation [24]. The flow chart of the genetic algorithm is shown in Figure 1.

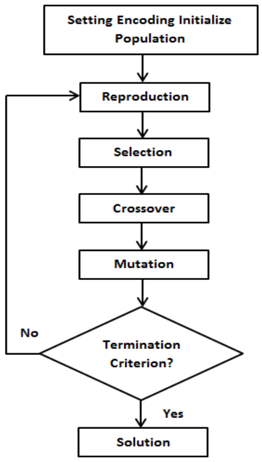

Figure 1: Flow of Genetic Algorithm

Besides the PID controller, cascade controller is widely used in the machine tools industry [25]–[31]. Cascade P/PI based on cascade controller is an established controller that is vastly used for precise positioning of machine tools. The controller consists of two loops; velocity and position loops. According to Jamaludin [32], velocity loop consists of a PI controller, notch filter, N(s) and the transfer function Vest(s). The function of these parameters is to estimate velocity signal from the measured position of encoder signal. The outer loop is a position loop where the characteristics of the open and closed loops are determined for the P controller value. The controller also has been further examined for position monitoring of direct current brushed motor [33]

III. Adaptive Nonlinear Control Strategies

A. NPID Controller

There are several advantages of the NPID controller in improving the precision of machine tools. The advantages are improving tracking accuracy, increasing the damping, reducing the rising time, and acting as friction compensation [34]–[37]. More importantly, Abdullah et al. [38] proved that NPID has lower Fast Fourier Transform (FFT) error compared to PID. Prior to this, Dong and Pedrycz [39] stated that an Approximation Grid Evaluation (AGE) of the NPID controller is feasible to be implemented in a feedback control problem. This showed the performance of the PID itself when combined with NPID or named as the cascade nonlinear gain. This method was developed to overcome the limitation of PID controller which is lack of self - tuning features. The AGE approach considers the index below:

$$J_{AGE}(F(\cdot)) = 1/\left[1 + \max_{k}(\varepsilon_k(F(\cdot)))\right] \quad (2)$$

Intelligent prediction algorithm is also implemented on the NPID controller by Zhang et al. [40]. The algorithm ensures fast convergence for higher error as well as improves in the tracking performance of Numerical Control (NC) positioning system.

B. ANPID Controller

ANPID is presented to compensate disturbances of nonlinear processes. Segovia et al. [41] suggested that the basic NPID controller is combined with the adaptive algorithm and associative memory. The validation on Programmable Logic Controller (PLC) with no special hardware and software showed that the robustness and performance of the controller are enhanced in the controlling time-invariant nonlinear plant. Moreover, the controller is implemented on the piezoelectric linear motor.

Subsequently, an adaptive nonlinear control technique was improved by Nuella et al. [42]. Figure 2 shows the system where the scholars considered two databases for the online tuning of PID parameters. The controller database shows the PID parameters and corresponding information vectors while modelling databases are useful for modelling principle where Just-in-time-learning (JITL) technique is implemented. It has been shown that the investigation of ANPID controller with additional elements of disturbance observer and dead-zone compensator is not done yet. The study of ANPID controller in catering disturbance forces of cutting and friction force still needs further improvement.

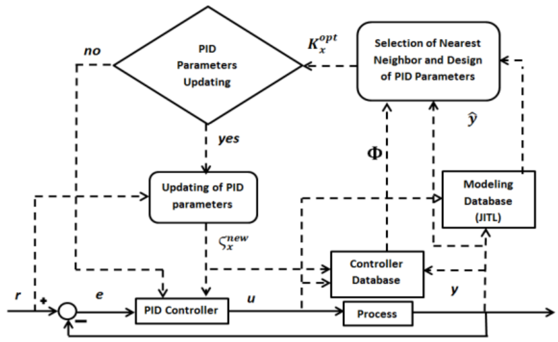

Figure 2: Adaptive PID for Nonlinear System

C. FNPID Controller

FNPID control strategy also has been proposed by past researchers [43]. The FNPID control strategy consists of Nonlinear PID (NPID) combined with Preisach model as it considers the overall hysteresis effect. For the open loop analysis, the hysteresis effect of 13.3% was obviously showed. With that, Table 1 shows the result based on several experiments where the first step is identifying the Preisach based on feedforward compensation and followed by three control strategies that are NPID, Feedforward PID (FPID), and FNPID. Based on the table, the scholars did closed loop analysis where they successfully reduced the hysteresis effect to zero with lower tracking error.

Table 1
Control Strategies Results

Control Strategies	Results
Preisach based feedforward compensation	2%
NPID	4%
FPID	1%
FNPID	0%

D. ARC

Robust and precision characteristics are crucial in designing adaptive nonlinear control system. Prior to this, an ARC for machine tools was designed by Al-Majed and Tomizuka [44]. The scholars claimed that the parameter variations are based on inertia, J and damping coefficient, B where the control law is presented below:

$$u = u_s + u_f, \qquad u_f = \hat{J}\left(\frac{1}{J_n}\mu - \lambda\dot{y}\right) + \hat{B}\dot{y} - \hat{F}_f - \hat{d}_l \quad (3)$$

Whereas, the adaptation law for both inertia and damping coefficient are:

$$\dot{\hat{J}} = Proj_J\left(-\Gamma_J\left(\frac{1}{J_n}\mu - \lambda\dot{y}\right)\right);\ \dot{\hat{B}} = Proj_B(-\Gamma_B\dot{y}) \quad (4)$$

Due to higher disturbances sensitivity and parameter variations, the proposed controller results in better tracking performance and transient response compared to the disturbance observer.

Despite this, Xu and Yao [45] comprehensively proved the ARC based on discontinuous projection. On the next year, they explored the idea of ARC using backstepping design to overcome both parametric uncertainties and uncertain nonlinearities [46]. As a result, the scholars have successfully reduced time consumption and costly rigorous offline identification. However, there is still loophole in terms of improvement for the ball screw drive system in catering deadzone phenomenon and both the cutting and friction forces.

E. NCTF Controller

NCTF is widely used for precise positioning of machine tools [47], [48]. For ball screw drive system, the friction produced during machining resulted in poor performance. NCTF with anti-windup integrator favourably reduced the overshoot and led to the improvement of the resolution requirements [49]. Next, an element of Acceleration-Reference – Continuous Motion (AR-CM) as implemented. According to Chong and Sato [50], the AR-CM is considered as the acceleration reference of motion besides velocity element where the controller leads to a high reduction in overshoot and disturbance parameters. The control law of controller, u is shown below:

$$U(s) = \left(K_p + \frac{K_i}{K_s}\right) U_p\ (s) \quad (5)$$

where;

$$U_p\ (s) = \ (E(s)s - \ E_{NCT}\ (s)s) + \ (E(s)s^2 - \ E_{\delta}(s)s^2)\gamma \quad (6)$$

$$E(s)s = \left(X_r\ (s) - X(s)\right)\frac{s}{1+T_d s} \quad (7)$$

$$E(s)s^2 = \left(X_r\ (s) - X(s)\right)\left(\frac{s}{1+T_d s}\right)^2 \quad (8)$$

Despite this, the improvement of NCTF for the cutting force produced during machining can be further discussed and analysed for both linear and ball screw drive system.

F. Fuzzy and Neural Network Control

Recently, fuzzy and neural network strategies are extensively used in positioning of machine tools. The scope is not limited to certain issues such as thermal error [51]. Based on latest improvement, the usage of fuzzy modal and neural network is focused on adaptation of PID controller. As mentioned by Savran and Kahraman [52], the conventional PID controller is hardly used for nonlinear environment. Therefore, the scholars came out with the idea of developing an adaptive tuning method. The adjustment method of the controller gains is done online using fuzzy predictor. Figure 3 shows the PID control scheme using the fuzzy method mentioned earlier.

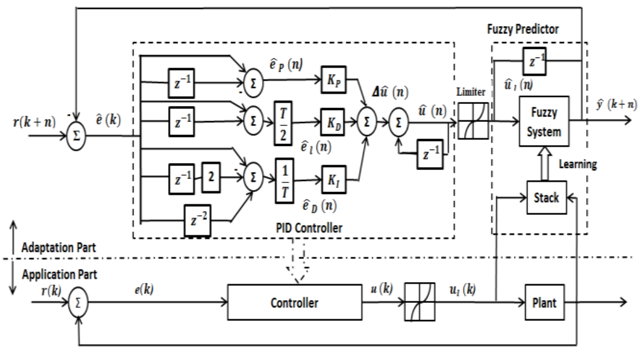

Figure 3: PID Controller using Fuzzy Model

Besides that, the usage of neural network is crucial for improvement of PID controller. The objective of the neural network control is to lowering the error. Kang et al. [53] pointed out the combination of PID with feedforward neural network. The scholars presented two neurons of input layer as shown below:

〖out〗_q1^1 (k)= x_q (k) (9)

〖out〗_q2^1 (k)= y_q^* (k) (10)

Equally important, there are hidden layer that consists of three neurons. The neurons are proportions, integrations and differentiation. The scholars miraculously proved that the designed controller leads to high accuracy, fast convergence speed and reliable stability for nonlinear system.

However, the recently research is done on both fuzzy and neural network control by El-Sousy [54]. The new technology showed the combination with several components for ensuring the stability, robustness, and optimality. The components include a mixed H_2/H_∞controller, a Self-Organizing Recurrent Fuzzy Wavelet-Neural-Network Controller (SORFWNNC) and a robust controller. The designed SORFWNNC consists of six layers. The layers are input, membership, rule, recurrent, wavelet and output layers where the output of the controller is written as follows:

$$U_{QS}^{SORFWNNC} = \Theta_{SORFWNNC}(E, \Phi, \sigma, \mu, b, c) = \Omega(E, \sigma, \mu, b, c) \quad (11)$$

Moreover, there is implementation of an artificial neural network (ANN) in machine tools. The genetic algorithm is used where Non-dominated Sorting in Genetic Algorithm (NSGA) is proposed for optimization of the ANN [55]. The algorithm is shown in Figure 4.

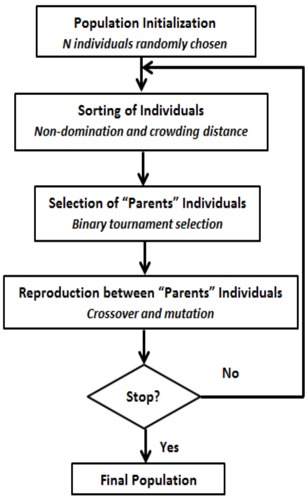

Figure 4: Optimization using NSGA Algorithm

IV. CONCLUSION

This paper presented an inclusive review of various nonlinear control strategies for the precise positioning of machine tools. Important conclusions have been obtained and are summarized as follows:

i. Precise positioning is crucial in machine tools industry. The nonlinear phenomenon must be considered in order to improve the precision, overall performance, and robustness of machine tools.
ii. The combinations of several control strategies successfully improve the precision of machine tools compared to stand-alone controllers.
iii. Current improvement of precise positioning for the nonlinearity of machine tools is focused on the implementation of the fuzzy and neural network [56], [57].

There are still problems and challenges regarding the nonlinear control strategy with several added modules such as deadzone compensator, feedforward compensator and disturbance observer that focus on both disturbance forces such as the cutting and friction forces. Research on precise positioning for nonlinearity of machine tools needs further development.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support by Universiti Teknikal Malaysia Melaka (UTeM) under the scholarship of 'Skim Zamalah UTeM', short term grant scheme (PJP) Universiti Teknikal Malaysia Melaka with reference number PJP/2014/FKPPROTOTAIP/S01379 and FRGS grant with reference number FRGS/1/2016/TK03/FKP-AMC/F00320.

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