Design and Implementation of fuzzy-based PID controller

M. J. E. Salami[*] and Yusuf. I. Bulale
Department of Mechatronics Faculty of Engineering
International Islamic University Malaysia
* *momoh@iiu.edu.my*

Abstract

Conventional proportional integral derivative (PID) controller is widely used in many industrial applications due to its simplicity in structure and ease of design. However, it is difficult to achieve the desired control performance in the presence of unknown nonlinearities, time delays, disturbances as well as changes in system parameters. Consequently several PID models have been suggested so at to alleviate these effects on the performance of the PID controllers. One such method is based on fuzzy logic technique which is considered much more appropriate when precise mathematical formulation is infeasible or difficult to achieve. Furthermore, some applications such as semiconductor packaging, computer disk drives, and ultra-precision machining require a fast and high precision processing. Consequently, there is the need to consider digital signal processor (DSP)-based fuzzy PID for use in such applications. Design and implementation of such technique is proposed in this paper. Results of simulation studies have demonstrated the feasibility of this controller since it produces fast response with smooth motion control.

Keywords: Fuzzy logic, PID controller, DSP, motion control.

1. Introduction

Industrial motion control is of paramount importance in increasing productivity and quality product as well as in reducing energy and equipment maintenance costs. Most of the research work in this area has always been focussed on improving the system performance with respect to the reduction of transient and steady state position errors. Although the overall system performance has improved over the years, position inaccuracy and time delay still exist. These problems manifest themselves in almost all motion applications resulting in imprecise or poor product quality or system response.

In order to achieve high-precision and high-speed motion control, uncertainty parameters such as friction, inertia and time delay must be accurately compensated for in the real-time motion control algorithm. Several control strategies have been proposed in the literature to overcome the above-mentioned problems [1-8]. Each strategy has its merits and demerits. A comparative study of some of these techniques has been discussed in [9].

It is well known that control techniques such as PID, sliding mode, LQR, and adaptive controllers have many advantages, however, these controllers can not effectively cope with nonlinearities since basically they do not possess the ability to incorporate existing human knowledge into their algorithms [10]. Their control algorithms are based on precise mathematical models that are usually difficult to achieve owing to the system complexity, nonlinearity, uncertainty, and time varying nature [11]. Besides that, when several different control techniques are available for a plant, the conventional approaches do not provide a direct way to decide when or whether to use a particular control technique without the intervention of human expert [10]. For these reasons, it is necessary to investigate new ways to overcome the difficulties posed by the conventional control techniques.

Intelligent control, in form of fuzzy logic, artificial neural network, genetic algorithm and expert system, has the learning, memory and reasoning capability and adaptability. This is a knowledge-based controller with reasoning mechanism rather than relying solely on the system mathematical model. Consequently, this can solve problems encountered in the use of the conventional controller such as unknown system parameters and their variation or noise perturbation as well as lack of reasoning or multiple control decisions [12]. Among these intelligent techniques, it appears those based on fuzzy logic (FL) perform better in terms of reduced mathematical model complexity and fast real-time operation as well as being least affected by parameter uncertainty or fault tolerance as compared to other techniques [9]. Furthermore, Fuzzy logic controller (FLC) has been successful used in many industrial applications and has shown significant performance and improvements over other controllers, especially in dealing with complex systems. However, there is still reluctance in some industries to adopt its use for control applications due to lack of systematic tuning procedure. Other significant reason can be little practical guidance on the design of fuzzy control as well as limited research work on the closed loop stability of the Fuzzy logic controller (FLC) systems [11]. In this paper a fuzzy-based PID controller is proposed in order to improve the performance of the conventional PID controller. The proposed system is implemented using DSP to ensure fast response that is needed for motion control applications. Results of simulation studies have shown the effectiveness of this controller in terms of reduced overshoot, fast response

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and reduced settling time as compared to the conventional techniques.

This paper is organized as follows. Section 2 presents the fuzzy-based PID controller while section 3 discusses the simulation studies. Hardware implementation and experimental results are discussed in section 4 whereas the summary of this study is given in section 5.

2. Fuzzy-based PID Controller

Despite the vast advances in the field of control engineering, PID still remains one of the most commonly used control algorithms in industry today. It is widely used because of its versatility, high reliability, and ease of design [13]. A PID controller is described by

$$u(t) = K_p e(t) + K_i \int e(t) d\tau + K_d \frac{de(t)}{dt} \qquad (1)$$

where K_p, K_i, and K_d are the proportional, integral and derivative gains respectively, u(t) is the output of controller; e(t) is the error signal. Using the trapezoidal approximation, a discrete form of (1) is given by

$$u(k) = K_p e(k) + TK_i \sum_{n=0}^{k} e(n) + \frac{K_d}{T}\{(\Delta e(k))\}, \qquad (2)$$

where $e(k) = y_r(k) - y_p(k)$; $\Delta e(k) = e(k) - (k-1)$; T is sampling time and $y_r(k)$, $y_p(k)$ and $u(k)$ are set-point, process output and controller output respectively.

The Ziegler-Nichols method has been known to be a fairly accurate heuristic method to accomplish the adjustment procedure of the PID controllers. The goal of tuning the system is to adjust the gains so that the system will have optimal performance under dynamic conditions. As stated above, the usefulness of this method is somehow limited for some applications. In order to improve the performance of the PID tuning, a fuzzy-based PID controller, shown in Figure 1, is proposed in this paper. This hybrid system uses the reference or command input y_r and the plant output y_p to generate a fuzzy output y_f according to

$$\begin{aligned} e(k) &= y_r(k) - y_p(k), \\ \Delta e(k) &= e(k) - e(k-1), \\ y_f(k) &= N_u f[N\Delta e(k), N_e e(k); \end{aligned} \qquad (3)$$

where N_e, $N_{\Delta e}$, *and* N_u are scaling factors for $e(k)$, $\Delta e(k)$, and $u(k)$, respectively; $e(k)$ is the tracking error between the reference input $y_r(k)$ and the output $y_p(k)$; and $\Delta e(k)$ is the change in tracking error. For this scheme, the PID controller is described by

$$u(k) = K_p e'(k) + TK_i \sum_{n=0}^{k} e'(n) + \frac{K_d}{T}\{e'(k) - e'(k-1) \qquad (4)$$

where é (k) = $y_f(k)$.

The adjustable gains $N_{\Delta e}$, N_e, and N_u are to ensure adaptation of the range of variation of quantities to universe of discourse and these are based on the hardware specifications and system requirements. The output of the summer, é, modifies the PID gains and as such the fuzzy logic is able to achieve the desired compensation.

2.1 Parameter tuning

The main issue of this controller is the ability to effectively and efficiently tune the control parameters. Each control process has different dynamic characteristics, and the controller parameters must be tuned accordingly. In this design, fuzzy controller tunes the PID parameters such that the required performance is achieved. Different attempts have been suggested on how FLC can modify the PID parameters, that is, how to select F_P, F_I and F_D to adjust the PID parameters,, where F_P, F_I and F_D are fuzzy parameters responsible for tuning the PID gains K_p, K_i, and K_d respectively. It is therefore possible to modify any one, or two or all the three parameters at same time. This control scheme is similar to the set-point modification used in [14]. A more general structure is to modify the set-point such that the nonlinear functions F_p, F_i , and F_d, would be the same and therefore be modified at the same time is proposed here.

The critical issue here is to design this nonlinear function *F* in equations (3) and (4) using a set of fuzzy rules. The design of fuzzy logic controllers involves the appropriate definition of a parameter set. This includes the inputs and outputs of the fuzzy logic controller, the number of linguistic terms and the respective membership functions for each linguistic variable, the inference mechanism, the rules and the fuzzification and defuzzification methods. In addition to the control performance specifications, implementation limitations such as software memory size and execution speed must be considered. Hence, it is necessary to keep tuning mechanism for the fuzzy logic unit simple.

2.2 Shape of membership functions

In the first fuzzy logic phase, fuzzification and actual measured input values are mapped into fuzzy membership functions. These membership functions are defined by both range of values and a degree of membership. The shape depends on the characteristics of the system to be controlled. Regardless of the process dynamics, the shape of membership functions for inputs and output are fixed for the same reasons as fixed rules. The membership function used for the inputs, e and ė are of triangular shape. This type of membership function is preferred because of its simple form and computational efficiency. The membership functions of the output are singleton types.

2.3 Rule tuning

The essential part of the fuzzy logic controller is a set of linguistic rules. In many cases it is easy to translate an expert's knowledge into such rules. Any number of rules can be created to define the actions of the fuzzy controller.

The suggested set of rules is shown in Table 5.1.

e **ė**	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NS	NM	NB	NB	NB	NB	PB
NM	NB	NM	NS	NM	NB	NM	PM
NS	NB	ZE	ZE	NS	NM	NM	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NM	PS	PS	PM	PM	PM
PM	NB	NM	NM	PM	PB	PB	PS
PB	NB	NM	PM	PB	PB	PB	PS

Table 5.1 sets of rules.

2.4 Defuzzification

After the fuzzy logic controller evaluates inputs and applies them to the rule base, it must generate a usable output to control the system. The fuzzy logic controller must convert its internal fuzzy output variables into crisp values that can actually be used by the controlled system. We can perform this portion of the fuzzy control algorithm, known as defuzzification, in several ways as mentioned earlier. Weighted average method is used in this design, that is,

$$\text{weighed average: } y = \frac{\sum w_i z_i}{\sum w_i} \qquad (5)$$

where z_i is the characteristic value of set i, w_i is degree of truth that set i applies, and y is defuzzified output. This type of defuzzification method has the advantage of simplicity and fast computation as compared to other defuzzification techniques.

As observed from the above discussions, the designed fuzzy model is TSK method which has triangular membership functions for the inputs, error (e) and change of error (ė), and singleton membership functions for the output, u. It has 49 rules. This fuzzy will supervise or tune the PID controller.

3. Simulation studies

Simulation studies of the designed Fuzzy-based PID controller are carried out in order to investigate its practicability. In this study, the actuator has the transfer function

$$G(s) = \frac{9.63}{s^3 + 1.5598s^2 + 75.7s} \qquad (6)$$

in which the constants in this equation depend on the motor specifications. Simulation of the controller was carried out using MATLAB/FUZZY-SIMULINK packages. The simulation results of the conventional PID and fuzzy-based PID controllers comparison is shown in Figure 2. Control performance is specified according to percent overshoot (POS), settling time t_s and steady state error e_∞. Outputs of both conventional PID and fuzzy-based PID controllers are compared by using (a) step and (b) square wave input excitation. To ensure reasonable comparison, the same gain parameters are used for both fuzzy-based PID and PID controllers, that is, the three parameters namely Kp, K_i, and K_d have been set to the same value for both controllers.

Tuning of the PID parameters is based on using Ziegler-Nichols rules. The best-tuned PID controller is selected and its performance is compared with the fuzzy-based PID controller. In this case, the best parameters for the PID are as follows: $K_p = 10$, $K_i = 15$, and $K_d = 1$. Using other values for the PID parameters would lead to either unstable situation or an increase in the POS and settling time.

Figure 2 shows the output responses of the hybrid controllers. As can be seen from this figure, Fuzzy-PID controller performs better than other hybrid controllers in terms of settling time, POS and steady-state error. As previously reported [16], the error of the fuzzy-based PID controller is equal to zero in the steady-state. For this reason, Fuzzy–PID was selected for this application. Figure 3 shows the output responses of the hybrid controllers for square wave input excitation. As shown in this figure, the tracking error of the hybrid controller is zero except for small negative error which could not be practically eliminated. Thus, the hybrid controller gives good tracking trajectory with good response and minimum (tolerable) error as shown in this Figure. This indicates the possibility of high positioning repeatability when used in practical systems. In practical applications, this can be X-Y table where X-axis can move some distance and stopped to later move in the direction of Y-axis. Also it can be different movement actions within the same axis but at different speed. In all multitasking actions a synchronous or interrupt service is needed to avoid any possible error. The results obtained have confirmed the possibility of a very good performance and fairly robust trajectory tracking when this proposed technique is used for control.

4. Fuzzy-based PID Controller Implementation

The hardware implementation of the hybrid controller is shown in Figure 4. The hybrid controller consists of: DSP controller, TMS320LF2407 [15], host computer, motor with attached encoder, H-driver, SN754410, inverter, 74LS04, and power supplier, 30V (max).

The source codes that have been used to test the designed hybrid controller were loaded to the DSP chip for testing as shown in Figure 4. Based on this set up, the system was run so as to check the performance of the controller. However, the system was not functioning properly so it was necessary to debug the system. It was discovered that Timer 2 and Timer 4 were not functioning. This problem was solved by setting either Timer 2 or Timer 4 to the internal clock rather than using the QEP clock. Another way to test the feasibility of the controller is by importing simulation data into the DSP-based hybrid controller and comparing the outputs. This approach is implemented in this study.

In all cases, the obtained simulation results are compared with the results obtained from hardware implementation of the fuzzy-based PID controller. Different cases were tested and a typical result is shown in Figure 5.

Figures 5(a) and (b) show the Fuzzy-based control output of the DSP (hardware) and simulation respectively for the pulse wave input excitation. Both Figures track the input signals although they have little delay sparks at the beginning of each change of the track. This result shows how the controller will control the plant and bring output to zero when ever the desired input signal is reached. In all cases fast response and smooth motion control were achieved. The results demonstrated the effectiveness and practicability of the fuzzy- based hybrid controller implemented using DSP.

5. Conclusion

The simulation results have shown that the proposed fuzzy-based PID controller can perform better than the conventional PID controller in all cases considered in this studies. These results have demonstrated that the fuzzy-based PID controller can be used to enhance the performance of conventional PID controller so as to overcome their inherent limitations such as the presence of unknown and severe nonlinearities.

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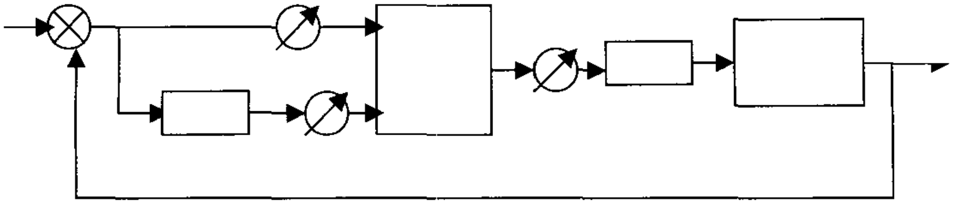

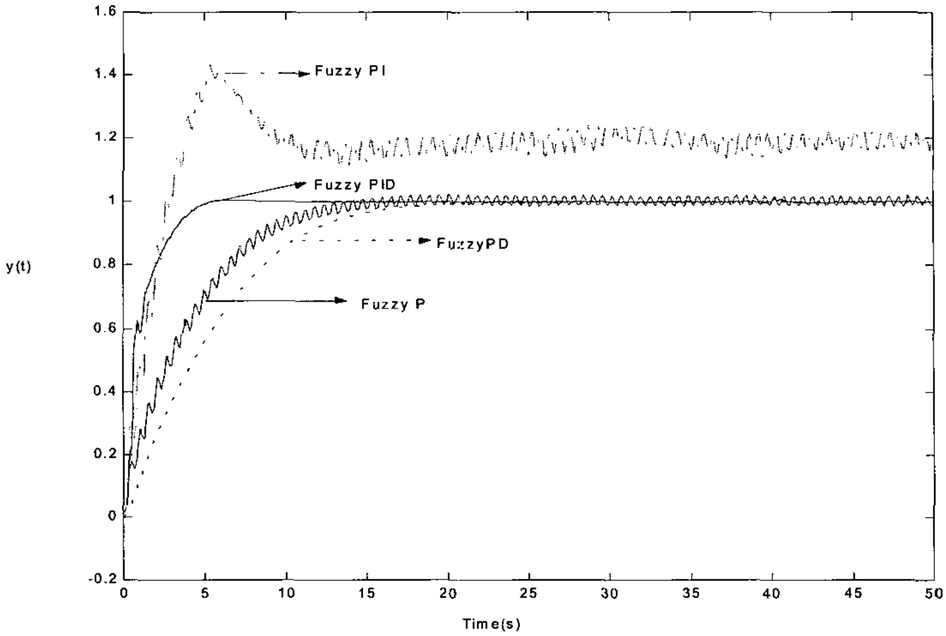
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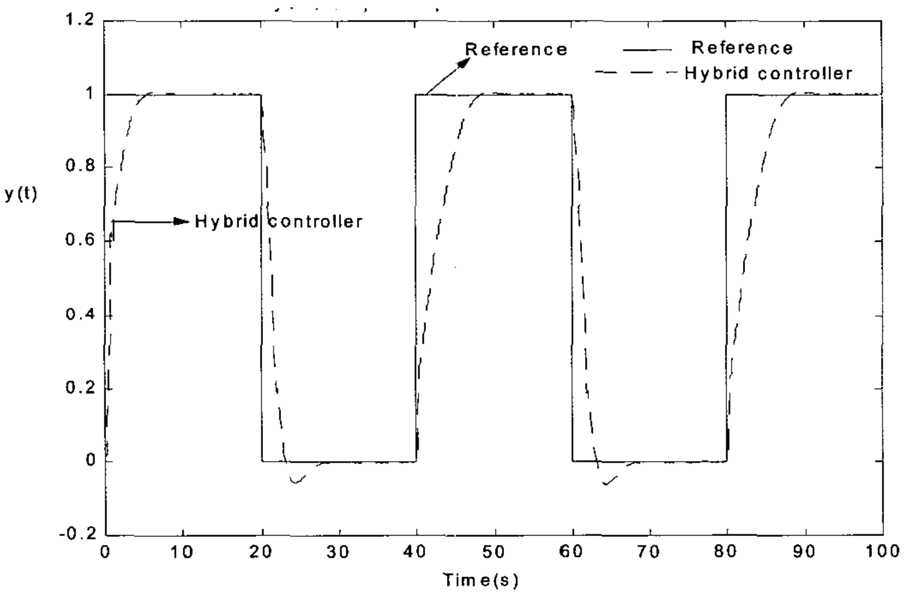
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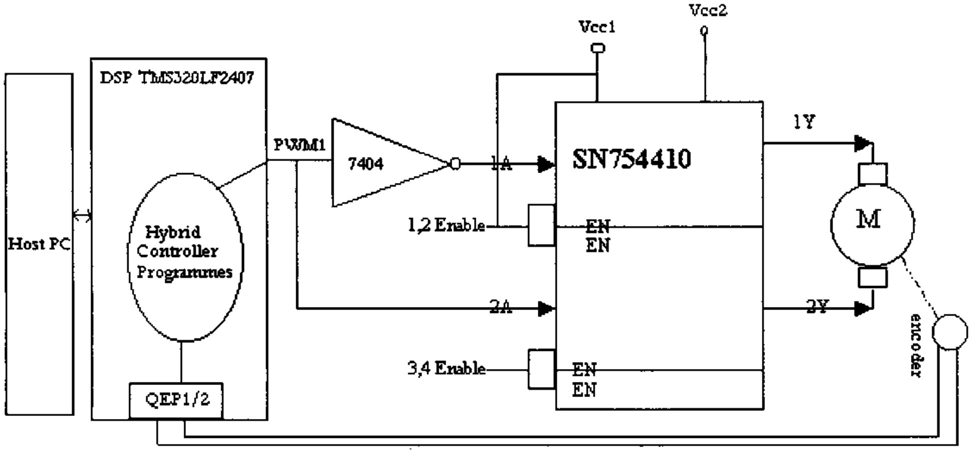
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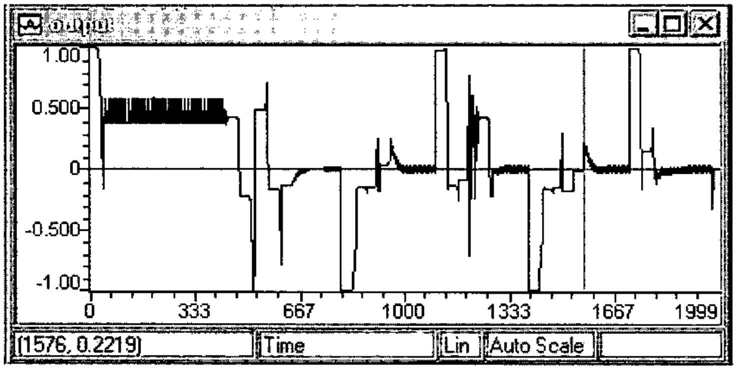
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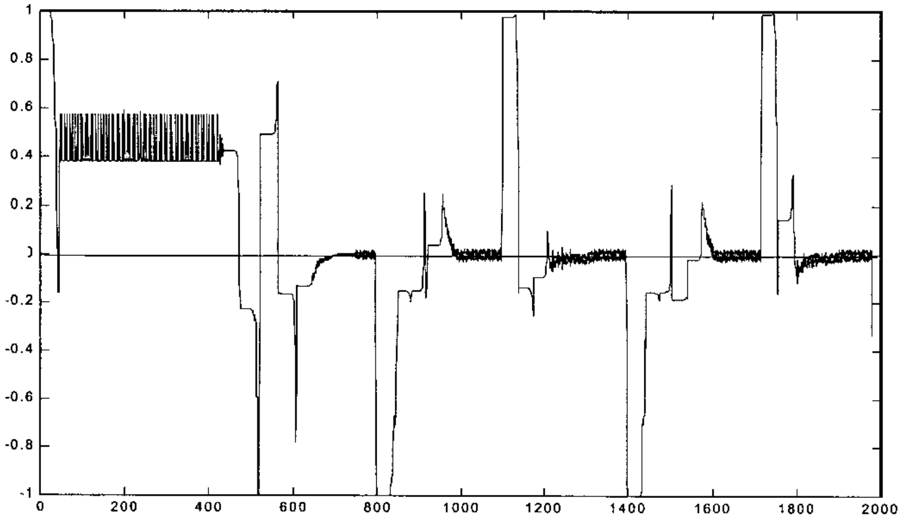
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