Design and development of DSP-based hybrid controller for servo driver applications

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Design and Development of DSP-based hybrid Controller For Servo Driver Applications

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***Abstract*– A hybrid system involving the conventional proportional-integral-derivative (PID) controller and fuzzy-logic system for servo drivers needed in many motion control applications is examined in this paper. The importance of this approach is the tuning of PID controller using fuzzy logic system, which by so doing enhances the performance of conventional PID controller in terms of settling time, percentage overshoot and steady-state-error. Thus, this proposed system is meant to compensate for the poor performance of the PID controller as a result of various factors such as unknown nonlinearities, time delays, disturbances as well as changes in system parameters. The second part of this work is the implementation of the hybrid controller using digital signal processor (DSP) as this offers high speed, number crunching capability and the ability to produce a good accurate tracking with minimum time delay for many industrial applications such as power inverters, motion controllers, semiconductor packaging, computer disk drives, packaging assembly, high speed, high precise motion of material transfer and automotive control applications where some of these applications may require a fast and high precision processing. Both simulation results and hardware implementation of the proposed controller have shown the feasibility of this approach as it produces fast response and smooth motion control.**

***Index Terms*-- DSP, Fuzzy logic, motion control, PID controller, servo drivers.**

I. Introduction

Industrial motion control is of paramount importance in increasing productivity and quality product as well as in reducing energy and equipment maintenance costs. Industrial servomotor drivers have developed through a remarkable combination of mechanical, electrical, power electronics and microelectronic technologies. Most of the research work in this area has always been focused 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 control (FLC) has been successfully used in many industrial applications and has shown significant performance and improvements over other controllers, especially in dealing with complex systems.

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However, there is still reluctance in some industries to adopt its use for control applications due to lack of systematic tuning procedure. Other significant reasons are large amount of parameters to be tuned [13] and 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]. Recently, fuzzy logic and conventional techniques are combined to realize hybrid control system so as to drive benefits of both methods. Several fuzzy-based hybrid control strategies [6, 10-13] have been proposed to improve the performance of the PID controller. In spite of their differences either in structure or tuning procedure or parameters with different applications, they share the same objective that is, to improve performance of the conventional PID controller. In this paper, hybrid controller, which is shown in Figure 1, is proposed in order to improve the performance of the conventional PID controller.

This hybrid controller is suggested so as to compensate the errors associated with PID controller in order to achieve

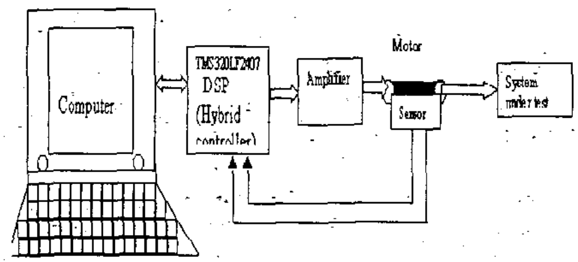

Fig. 1 System block diagram

improved (better) accuracy as well as to attain fast response for the desired motion. In this paper, the fuzzy system is designed to supervise the PID controller in order to improve the dynamic response of the closed-loop system. In addition, this approach can be used to minimize the tracking error due to the friction, other disturbances or any uncertainty of the system. DSP is used in the implementation of this system since it has higher and fast computational power, flexibility, and the ability to produce accurate tracking with minimum time delay. Results of simulation studies have shown the effectiveness of this controller in terms of reduced overshoot, fast response and reduced settling time as compared to the conventional techniques.

This paper is organized as follows. Section 2 presents the hybrid controller design while Section 3 discusses the simulation studies. Hardware implementation and experimental results are discussed in Section 4 followed by the summary of this study in section 5.

II. HYBRID CONTROLLER DESIGN

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, easy understanding, and ease of design [14]. Assuming that the input to the PID controller is error, e(t) and output is, u(t), the equation defining the operation of the PID controller is given by

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d(\tau) + K_d \frac{de(t)}{dt} \qquad (1)$$

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, $e(t) = y_r(t) - y_p(t)$, $y_r(t)$ is the desired value and $y_p(t)$ is the actual output. 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 $\Delta e(k) = e(k) - e(k-1)/T$; T is sampling time.

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 (due to plant parameter variations or operating conditions change). In order to improve the performance of the PID tuning, a fuzzy-PID controller, shown in Figure 2, is proposed in this paper.

It is required now to map the rule base to the discrete state space change-in-error $\Delta e(k)$ and error e(k). Scale factor are required for some applications for the universe range, N > 0. This scale factor sets the universe ranges for the error and change-in-error.

Applying fuzzification to equation (2) and then defuzzifying it, we get the equation

$$u(k) = ND\{F\{\frac{1}{N} K_p e(k) + \frac{1}{N} TK_i \sum_{n=0}^{k} e(n) + \frac{K_d}{NT} \Delta e(k)\}\} \qquad (3)$$

where D and F are defuzzifiation and fuzzification, respectively. The proposed hybrid compensator is based on equation (3), which is shown in Figure 2.

This hybrid system uses the reference or command input y_r and the plant output y_p to generate a fuzzy output y_f. 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

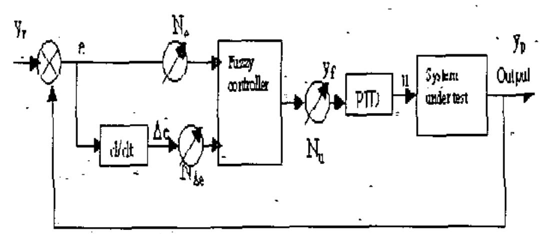

Fig. 2 Hybrid control structure

requirements. The output of the summer, é, modifies the PID gains and as such the fuzzy logic is able to achieve the desired compensation.

a. Parameter tuning

The main issue of this controller is the ability to effectively and efficiently tunes 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 errors associated with PID is compensated to achieve the required performance. 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 [15]. 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 equation (3) 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. Aside from 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.

b. 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. 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 while the membership functions of the output are singleton types.

c. 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 I.

TABLE I
SETS OF RULES

ė \ e	**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

d. Defuzzification

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. Weighted average method is used in this design, that is, weighed average:

$$y = \frac{\sum w_i z_i}{\sum w_i} \tag{4}$$

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-in-error (ė), and singleton membership functions for the output, u. It has 49 rules. This fuzzy will supervise or tune the PID controller.

III. SIMULATION STUDIES

Simulation studies of the designed Hybrid controller are carried out in order to investigate its practicability. In this study, the servo actuator has the following main parameters are shown in Table II.

TABLE II
SERVO DRIVER PARAMETERS

Parameter	Value
Inertia load, j	**0.214Kgm^2**
Motor resistance, R	**7.8 Ω**
Motor inductance, L	**5.0mH**
Motor torque constant, K	**9.0 Ncm/A**
Back-emf constant, K	**9.0Vs/rad**
Output power	**30 W**

Based on these parameters, the simulation of the system was investigated. Simulation of the controller was carried out using MATLAB/FUZZY-SIMULINK packages. Control performance is specified according to percent overshoot

(POS), settling time t_s and steady state error e_{ss}. Outputs of both conventional PID and hybrid controllers are compared by using (a) step and (b) square wave input excitation. To ensure reasonable comparison, the same gain parameters are used for hybrid and PID controllers, that is, the three parameters namely K_p, K_i, and K_d have been set to the same value for both controllers.

Tuning of the PID parameters initially is based on using Ziegler-Nichols oscillation tuning method. The best-tuned PID controller is selected and its performance is compared with the hybrid 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 3 shows the output response of three hybrid controllers and as suspected the hybrid (fuzzy + PID)

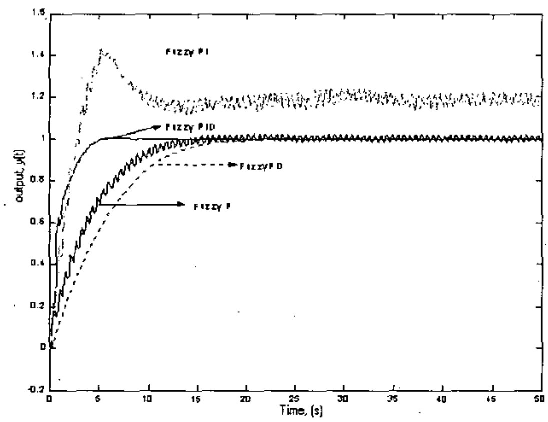

Fig .3 Output response of the hybrid controllers

controller gives best performance compare to other hybrid controllers in terms of settling time, overshoot and steady state of error. Figure 4 shows the output responses of the hybrid controller for square wave input excitation. As shown in this figure, the tracking error of the hybrid controller is zero

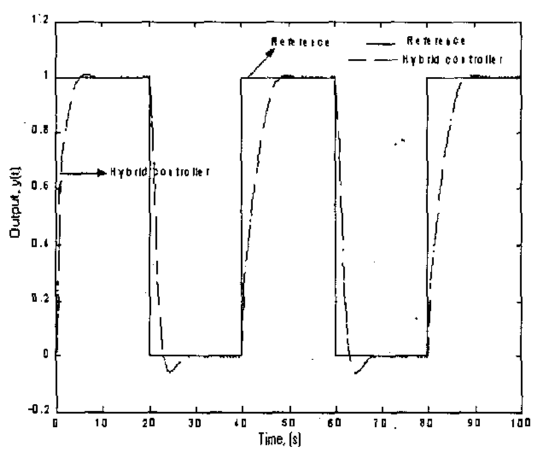

Fig 4 Output response of the proposed hybrid controller

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. This hybrid controller was also compared with the conventional PID controller. Figure 5 shows comparison

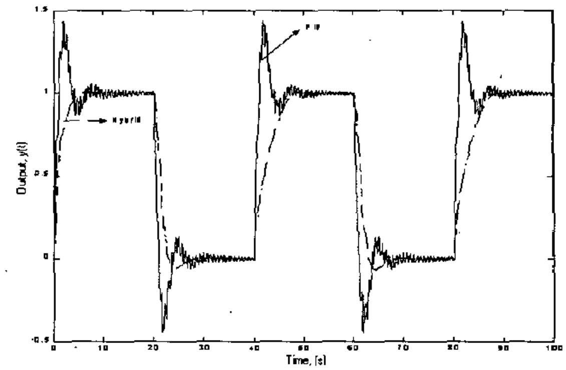

Fig5 Hybrid and PID controller comparison (square wave input)

of conventional PID and hybrid controllers with square wave excitation. As can be seen from this figure, hybrid controller performs better than conventional PID controller in terms of tracking and overshoot. The obtained results have confirmed the possibility of a very good performance and fairly robust trajectory tracking when this proposed technique is used for control.

IV. HYBRID CONTROLLER IMPLEMENTATION

The hardware implementation of the hybrid controller is shown in Figure 6. The hybrid controller consists of: DSP controller, TMS320LF2407 [16], host computer, motor with

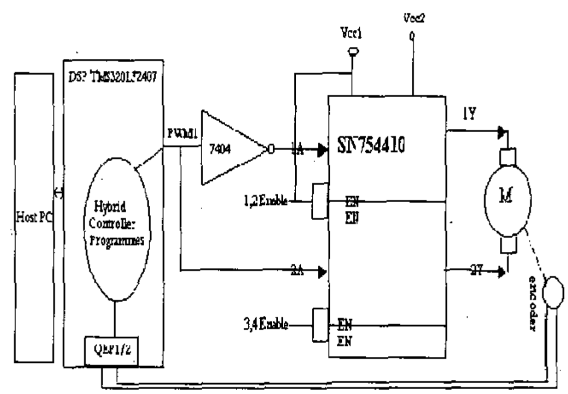

Fig 6 Hybrid controller implementation

attached encoder, H-driver, SN754410, inverter, 74LS04, and power supplier, 30V (max). The DSP controller implements the servo compensator algorithms and it is responsible for communications with the host system, measuring the motor position and producing the drive signal sent to the driver. The sampling time for this system was set to 1 ms. The servo compensator for this system is hybrid algorithm. The position of the motor is controlled by PWM, which is generated in the system using on board PWM module of the TMS320LF2407. A driver circuit is required to convert the PWM output into a range of voltages and currents suitable to run the servomotor and to provide protection from transients generated by the motor.

The source codes that have been used to test the designed hybrid controller were loaded to the DSP chip as shown in Figure 6. Based on this set up, the system was run so as to check the performance of the controller. To test the feasibility of the controller, the data simulation is imported into the DSP-based hybrid controller and compared 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 hybrid controller. Different cases were tested and a typical result is shown in Figure 7 and Figure 8.

Figures 7 and 8 show the hybrid controller output of the

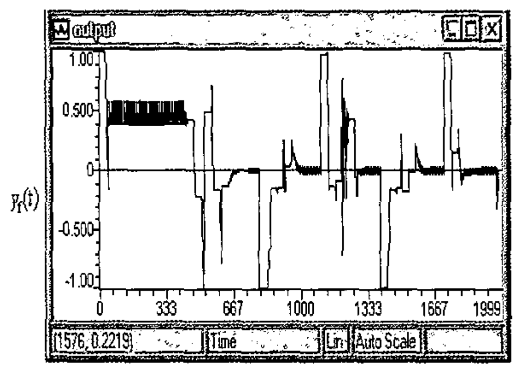

Fig.7 DSP Hybrid controller output

DSP (hardware) and simulation respectively for the pulse

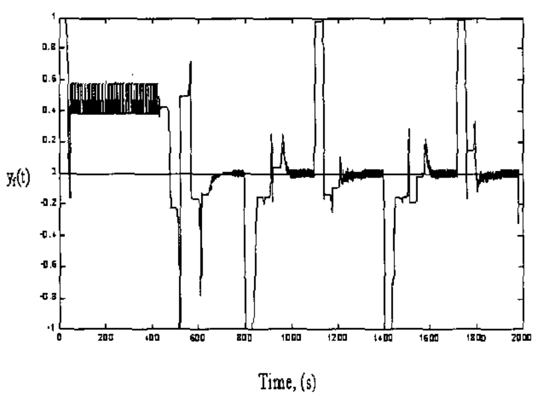

Fig. 8 Hybrid Simulation controller output

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 whenever 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 hybrid controller implemented using DSP.

V. CONCLUSION

The simulation results have shown that the proposed hybrid controller can perform better than the conventional PID controller in all cases considered in this study. Results obtained from the hardware implementation and simulation studies have demonstrated that the hybrid controller can be used to enhance the performance of the conventional PID controllers so as to overcome their inherent limitations such as the presence of unknown disturbances and severe nonlinearities.

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