Real time implementation of time delay controller for DC motor speed control

G.S. Hyalij, A.U. Deshpande , P. D. Shendge , B.M. Patre

Abstract—This paper deals with real time implementation of different controllers i.e., feedback, PID, Time Delay Control (TDC) for DC motor speed control. Control algorithms like state feedback, Proportional Integral Derivative (PID) are the basic algorithms used for controlling linear time invariant (LTI) system and fail for nonlinear and uncertain system, TDC being a robust controller can overcome limitations of simple feedback, PD and PID algorithm. This paper shows how TDC works as a robust controller when DC motor input has an external disturbance. Here simple feedback, PID and TDC controller are implemented and results are compared. Time delay control is the approach used for the estimation of uncertainties and disturbances which works on assumption that the error at present instant is equal to error at previous instant. These algorithms are implemented on SPARTAN-3E Field Programmable Gate Array (FPGA) instead of microprocessor or DSP where VHDL is used.

I. INTRODUCTION

With only the classical Proportional Integral plus Derivative (PID) controller applied to control of a DC motor, a good performance characteristic of the controller can be obtained, if all the model parameters of DC motor and operating conditions such as external load torque, disturbance etc. are exactly known. However, in case when some of system parameters or operating conditions are uncertain or unknown, the fixed PID controller does not guarantee the good performance which is assumed with precisely known system parameters and operating conditions.

Seung-Min Baek and Tae-Yong Kuc [1] designed an Adaptive PID Learning Control for DC Motors. In this paper the adaptation and learning concept for intelligent control is introduced in developing a PID tuning method for DC motors including external disturbances. V. Tipsuwornpoom et al [2] contribute the DC motor control by Binary Rate Modulation (BRM) instead of PWM or PFM which is accomplished by power transferring to armature to control motor speed. The 8 bit binary rates are controlled by 8051 which turn generate BRM by PI (Proportional Integral Controller). Sameep Singh and Kuldip Rattan [3] implemented a fuzzy logic controller for the DC motor controller. They implemented a fuzzy logic controller (FLC) on a Field Programmable Gate Array (FPGA) using Very High Speed Integrated Circuit Hardware Description Language (VHDL) which is advantageous for the designer to make modifications easily and quickly. Gundogdu [4] designed a fuzzy logic controller to regulate the crank angular speed of the DC motor mechanism and compared to an optimal PID controller. Yoram Koren and S. Malkin [5] proposed torque and speed control of DC-servomotors for robots where the motor rotational speed is controlled by manipulation of the motor voltage. A new optimal sliding mode control scheme based on sliding mode control for DC motor speed control is proposed by Wang et al in which sliding mode surface designed is based on the augmented system.

In 1990 Toumi and Ito [6], [7] proposed on control of system with unknown and unexpected disturbances called Time Delay Control (TDC). Under the assumption of accessibility to all the state variables and estimates of their delayed derivatives, TDC is characterized by simple estimation technique that evaluates a function representing the effect of uncertainties and disturbances. This proposed control algorithm neither require any plant model nor does it depend on estimation of specific plant parameter. It uses information in the recent past to directly estimate the unknown dynamics at any given instant through time delay. Chang and Lee [8] designed observer for time delay control and its application to DC servomotor. He took this experiment on a DC servomotor and proved subject to substantial inertia variation and external disturbance, TDC controller gave robust performance.

Hardware Controllers can be implemented in many ways. Now in embedded world one of the important ways is use of an FPGA which is suitable for fast implementation and quick hardware verification. FPGA based systems are flexible and can be reprogrammed unlimited number of times. The FPGA consists of three major configurable elements; configurable logic blocks (CLBs) arranged in an array that provide the functional elements and implements most of the logic in an FPGA, input-output blocks (IOBs) that provide the interface between the package pins and internal signal lines, and programmable interconnect resources that provide routing path to connect inputs and outputs of CLBs and IOBs onto to the appropriate network. A digital design can be created by using schematic digital design editor that uses graphic symbols of the circuit or by using hardware description languages such as Verilog, Very High Speed Integrated Circuit Hardware Description Language (VHDL). One of the key features of using VHDL is that it can be used to achieve all the goals for documentation, simulation, verification and synthesis of digital designs, thus saving a lot of efforts and time. Different design entry softwares are available that can be used for modeling, verification and implementation of digital designs.

Chang et al [9] proposed reduced-order time delay control (RTDC) and they applied it to the position control of a brushless DC motor with a highly simplified hardware configuration: use of six-step commutation without current control unit. They have observed that RTDC effectively compensates for parameter variations, nonlinearities and the torque ripple caused by six-step commutation, where a conventional PID control cannot handle with adequate performances. A new control algorithm called the time-delay sliding mode control (TDSMC), based on the time delay control and the integral sliding mode control, is proposed and applied for controlling DC servos with a seal installed on their rotating axes is proposed by Park and Kim [10]. This algorithm adopts the robustness of sliding mode control and improves the robustness of the TDC. They show the results of a series of experiments on a DC servo motor system with stick-slip friction and proves TDSMC is compatible with the TDC in the nominal performance, but is superior to the time delay control and the PID control in the performance robustness. Fuzzy logic is combined with the robust structure of a time delay control [11] to show the performance evaluations through the control synthesis of a DC servo motor by Sae Kyu Nam. So fuzzy time delay control does not require the explicit mathematical model nor does it depend on the learning approach for adaptation. Real time implementation of continuous and discrete time sliding mode control using computer...
on inverted pendulum of Quanser is shown by Garcia et al [12].

Here an author implemented three different controller; feedback, PID and TDC controller for DC motor speed control on Spartan-3E Field Programmable Gate Array instead of microprocessor or DSP. Here VHDL program are in the black box which is one of the Xilinx blockset in Matlab Simulink. For Xilinx blockset, System Generator (SysGen) is used. The results for feedback, PID and TDC are compared. Simple DC motor with maximum of 12 volt and with 10 rpm speed, with an optical encoder on the top to give pulses according to the revolutions. Encoder gives 500 pulses per revolution. Input to motor has been given through the Digital to Analog converter on the Xilinx board.

In this paper a time delay controller with state feedback is proposed for DC motor control to achieve desired speed. The state feedback is to ensure the stability of closed loop system and incorporated time delay control enables the exact speed control of the command input despite external disturbance. Finally numerical and experiential works are performed to compare the performance of the proposed controller with conventional controllers.

This paper is organized as follows: In Sec. II mathematical modeling for DC motor is given. Feedback and PID controller is explained in Sec. III while in Sec. IV time delay controller design is discussed. Experimentation implementation and results are given in Sec. V and Sec. VI resp. In Sec. VII simulation results are given and finally it is concluded in Sec. VIII.

II. MATHEMATICAL MODELING FOR DC MOTOR

The mathematical model for the DC motor is given below. The voltage loop equation

\[ u(t) = L_a \frac{di_a}{dt} + R_a i_a(t) + e_b(t) \]  

\[ e_b(t) = K_b \omega(t) \]

\[ \frac{d\omega}{dt} = \left( -\frac{K_T K_b}{R_a J} - \left( \frac{B}{J} \right) \right) \omega(t) + \left( \frac{K_T}{R_a J} \right) u(t) \]

By considering \( \theta, \omega \) as the two states, the state space equation becomes

\[ \begin{bmatrix} \frac{d\theta}{dt} \\ \frac{d\omega}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\left( \frac{K_T K_b}{R_a J} \right) - \left( \frac{B}{J} \right) \end{bmatrix} \begin{bmatrix} \theta \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_T}{R_a J} \end{bmatrix} u(t) \]

III. CONTROLLER DESIGN

Three main control strategies which has been implemented here i.e. feedback, PID and time delay controller are discussed here.

A. Feedback controller

The simplest form of closed loop control in which output state speed is fed back to the input. The output is of motor is mechanically assembled through encoder. The encoder output \( (V_e) \) which is proportional to the speed of motor is fed back to FPGA where the reference input \( (V_r) \) is compared with encoder output and accordingly control signal is send through DAC to the motor for correct action.

\[ e_f = V_r - V_f \]  

where \( e_f \) error signal for feedback controller.

B. PID controller

It is the most widely used control algorithm. Generally PID controller gives satisfactory response. The main function of the proportional, integral and derivative is to provide adequate transient response, zero steady state error and improve closed loop stability and speed of response. Control law for PID controller can be given as below

\[ u = K_p e + K_i \int e dt + K_d \frac{de}{dt} \]  

where \( K_p, K_i \) and \( K_d \) are integral and derivative constants. As stated earlier proportional part \( K_p \) provides transient response. To remove steady state error we have to introduce integral controller. Integral system slows down response of the system. So derivative part come into play speed up response of system. Output from optical encoder is used to feed states back and compared with reference signal to pass through the PID control.

IV. TIME DELAY CONTROL

With the classical PID controller applied to control of a DC motor, a good (target) performance characteristic of the controller can be obtained, if all the model parameters known. The fixed PID controller does not guarantee the good performance when some of system parameters or operating conditions are uncertain or unknown. Most of the practical systems have system parameter variations and unexpected disturbances. In such situation, general methods like fixed-gain controller will be inadequate to achieve satisfactory performance in the entire range over which the system may vary. Adaptive control, sliding mode control, trial and error approach are some techniques to tackle this problem. Another way to design control is choice of bounded uncertainties in system parameter and input disturbance. This assumption of bounding makes control large due to nonavailability of the desired information about the range over which the uncertainties and disturbance vary. In view of this and robustness enhancement of DC motor control system, we propose time delay...
controller for DC motor speed control. This assumption of bounding makes control large due to no availability of the desired information about the range over which the uncertainties and disturbance vary. Time delay control is another method which can tackle uncertain systems. The idea underlying TDC is presented by Youcef-Toumi and Ito. Youcef-Toumi and Reddy in [6], [7], TDC depends on the direct estimation of a function representing the effect of uncertainties. It uses the past information of the system responses and control input to directly modify the control actions rather than adjusting the controller gains or identifying system parameters thereby leading to a model independent controller. It is possible to directly estimate the unknown dynamics at any given instant through the time delay. Consider a single input, single output plant

$$\dot{x} = Ax(t) + B(u(t) + d(x, t)) \quad \text{(8)}$$

$$y = Cx(t) \quad \text{(9)}$$

where $A$, $B$, and $C$ are known matrices, $d(x, t)$ is an unmeasurable disturbance signal, $x(t)$ is the state vector and $u(t)$ is control input. TDC estimates disturbance and is given by. Thus the best approximate solution of the equation is adopted to determine the control $u$.

$$u = B^+(\dot{x} - Ax - Bd) \quad \text{(10)}$$

**Assumption 1:** In order to obtain an estimate of the effect of the term $d(x, t)$, it is concerned that value of the function $d(x, t)$ at present time $t$ is very close to that of $(t - L_d)$ in the past for small time delay $L_d$.

$$d(x, t) \approx d(x, t - L_d) \quad \text{(11)}$$

From the dynamics of (8)

$$d = B^+(\dot{x} - Ax - Bu) \quad \text{(12)}$$

So

$$\dot{d} = B^+(\dot{x}(t - L_d) - Ax(t - L_d) - Bu(t - L_d)) \quad \text{(13)}$$

The TDC control law is then obtained from (10) and (13) as $u = -\dot{d}$

$$u = -B^+(\dot{x}(t - L_d) - Ax(t - L_d) - Bu(t - L_d)) \quad \text{(14)}$$

TDC does not depend on estimation of specific parameters, repetitive actions, infinite switching frequencies, or discontinuous control. It does not presume linearity. It employs fast observation of the system response and control inputs to directly modify the control actions rather than adjust the controller gains. It updates its observation of the system every sampling period; therefore, estimation of plant dynamics is dependent upon the sampling frequency.

V. Experimental implementation

A different controller like feedback, PID and time delay controller has been created using the software Simulink, SysGen. With the help of blockset in Simulink/Sysgen we have formed a model for each control which has been used to generate VHDL code. This code is then downloaded into FPGA Xilinx board. Then FPGA output is given to motor through Digital to Analog Converter (DAC) already provided on the same board. This motor is a simple DC motor with maximum 12 V with 10 rpm speed. An optical encoder is mechanically assembled with this motor which gives 500 pulsed per revolution.

VI. Experimental results

In this section simulations and experimental results are presented for all controller i.e. feedback, PID and TDC. Firstly, all the equipment used in this study are represented in fig. 1 are:

- PC Pentium
- Spartan-3E board with DAC
- Hardware setup of DC motor mechanically linked with encoder

It is assumed that all states are available to compute controller. However in the investigated DC motor system only one state $\theta$ is available. To calculate other state $\dot{\theta}$, we used derivative filter using MATLAB/Simulink/SysGen software. Initially simple step input as a input with 1.65 V and 0.825 V is applied. When non-disturbed input is applied the motor speed output for feedback, PID and TDC controller is shown in fig. 2-3 for 1.65 V input. But when disturbance is present, experimental results are shown in fig. 4-5 which shows feedback and PID controller does not guarantee the robustness w.r.t. the external disturbance. Fig. 4 shows input with disturbance and for this input feedback controller output for motor speed control. PID and TDC controller for the speed controller output is shown in fig. 5. By the analysis of the experimental results it is observed that the time delay controller play an important role when system have an external disturbance. The results indicate that the system performance was deteriorated as disturbance is added in the system. Time delay control estimate the disturbance and control performance is best when compared to feedback and PID. Fig. 4 and fig. 5 are the comparison of real time speed control for DC motor between feedback, Time Delay Control and PID with input wave at voltage level 1.65 which corresponds to 1.375 rpm for sampling time 1 sec. The actual input, disturbance and input after addition of disturbance is shown in fig. 6.

VII. Simulation

The simulation results are shown in fig. 7-10. The results considering a step input as a reference signal and initial condition $[\theta, \dot{\theta}] = [0, 0]$ are given. A nearly sawtooth disturbance signal is added as an external disturbance which can be easily observed from all simulation figures. The model given in eqn. 1 is used for simulation. Results are taken for sampling period of 1 sec with the reference input of 1.65 and 0.825 V. The simulations take into account that the control is accomplished using a computer. Two cases are shown here: one for different controllers for non-disturbed input and other when disturbance is present. Results
Fig. 2: Input and feedback controller output for nondisturbed input

Fig. 3: PID and TDC controller output for non disturbed input

Fig. 4: Input and feedback controller output for disturbed input

Fig. 5: PID and TDC controller output for disturbed input

Fig. 6: Actual input, disturbance and input after addition of disturbance

indicate system performance is deteriorated for feedback and PID controller a larger extent when external disturbance is presented. For no disturbance all three controllers function well. The fig 7-8 shows simulation results of DC motor speed control for different controller when speed is 1.375 rpm and sampling period is 1 sec without disturbance and fig. 9-10 shows same different controllers results when disturbance is present.

**VIII. Conclusion**

Experiments on DC motor speed control is presented here. Simulations and experimental results for feedback, PTD and TDC design are shown. The obtained results proved the effectiveness of the time delay controller over feedback and PID for disturbed system. By the analysis of the simulation and experimental results it is observed that the time delay controller play a key role when system have an external disturbance. The results indicate that the system performance deteriorates if disturbance is present. Time delay control estimate the disturbance and control performance is best when compared to feedback and PID. A Time Delay Control with state feedback is proposed for DC motor speed control and is proven to be very effective throughout the simulations and experiments.
Fig. 7: Simulation: Input and feedback controller output for non disturbed input

Fig. 8: Simulation: PID and TDC controller output for non disturbed input

Fig. 9: Simulation: Input and feedback controller output for disturbed input

Fig. 10: Simulation: PID and TDC controller output for disturbed input

REFERENCES


