Design and Implementation of Embedded Speed Controller on ARM for Micromanufacturing Applications

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***Abstract*—A robust and high precision control system has been designed in MATLAB for a prototype DC motor system running at high rpm with uncertainty in plant parameters and in the presence of plant disturbances and measurement errors. The controllers have been designed using variety of approaches PID, LQG, and LSDP. Each of these design in MATLAB meet rise time, settling time and peak percent overshoot as [0.0765 s, 0.403s, 11%], [0.019s, 0.0877s, 13.2%,], [0.153s, 0.637s, 9.36%], [0.153s, 0.632s, 9.36%] for PID, LQG, LSDP-I & II respectively. Simulation designs have been further hand tuned to get better results to achieve the required specifications. The digital implementation have been done on MCB2300 KEIL boards on ARM7 (32-bit) microcontroller using difference equation methods and controller performances have been evaluated.**

***Keywords*-Embedded Controller; Robust Controller;**

I. INTRODUCTION

The developments in power electronics and microprocessor/ microcontroller system and integrated application to process control area makes possible to implement control strategies for electrical drives which exhibit the high levels of quickness and precision, required for many applications, such as robot driving systems and Micromanufacturing. PWM signal based control is very fundamental to DC motor control system when implemented on digital. Other techniques applying hysteresis control, PI control, deadbeat control, predictive current control, and so on, have drawback of undesirable current fluctuation arising due to parameter variations. Therefore, taking account of the variations of motor parameters is essential [1], [2], [3], [4], [5]. In Micromanufacturing applications requirement form a control system is of high accuracy in controlling speed and high speed of response by the control system. The speed control ability of a DC motor system is affected by variations in parameter due to deterioration over the life span of the system and disturbance in load torque and signal noise. Since control system is based on mathematical plant model, and it is known that practically accurate parameter measurement is very difficult and parameters vary with operating conditions, therefore the controlling becomes a challenge under noise, disturbances and parameter variations. For these reasons motor control methods are applied which use the disturbance observer to compensate parameter variations and disturbance torque were proposed [6], [7], [8] . High-performance control of servo motor was achieved. The achievement of overall performance of a control system not only depends on the quickness and the precision of the system response, but also on the robustness of the control strategy that is its capability to ensure the same performances if exogenous disturbances and variations of the system parameters occur. In fact, online variations of parameters, such as, temperature variation, saturation and load imbalance etc. can affect the performances to degrade the results in Micromanufacturing applications. Robust controllers, from this point of view are very important and powerful tool for designing control systems under such uncertainties and variations [9], [10], [11], [12]. In this paper, high speed, high precision DC motor control system has been designed in MATLAB and implemented on ARM microcontroller. ARM microcontroller boards provide ample opportunity to program and control variety of tasks in parallel which very much essential in high speed manufacturing and control applications. It allows running in parallel sensing, evaluation and control modules while allowing some routine background tasks. The paper considers both conventional PID and robust controllers - LQG (linear Quadratic Gaussian) & LSDP (Loop Shaping Design Procedure). Digital implementation of these controllers has been done and their performances have been evaluated and compared.

II. DC MOTOR MODELING, ROBUST CONTROLLER DESIGN AND SPECIFICATION

The behavior of a dc motor can be described by the four equations stated below.

$$\tau(t) = K_m i(t) \tag{1}$$

$$J\dot{\omega}(t) = -K_f \omega(t) + K_m i(t) \tag{2}$$

$$v_{backemf}(t) = K_b \omega(t) \tag{3}$$

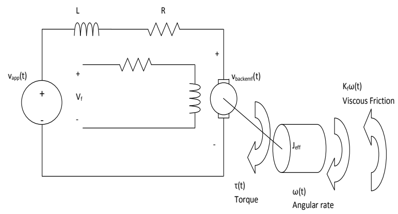

Figure 1. A parameter based representation of DC motor

$$v_{app}\left(t\right) = L\frac{di\left(t\right)}{dt} + Ri\left(t\right) + v_{backemf}\left(t\right) \tag{4}$$

A parameter based representation of a DC motor(Figure 1) driving an inertial load, shows the angular rate of the load, ω(t), as the output and applied voltage, v_{app} (t), as the input. Lab Prototype of a DC motor has been characterized with high computational precision on an embedded ARM (32-bit) system. Its parameters of interest have been measured and monitored online during its course of operation. The values obtained for the systems are 3.275026417×10^{-4} kg·m^2, 1.42419433×10^{-6} N·m·s, 7.6 ohm, 4.6 mH, 6.16×10^{-3} N·m/A and 6.16×10-3 V·s for inertia, friction coefficient, resistance, inductance, Torque constant and Back-EMF Constant respectively [13]. Second Order Transfer Function obtained from modeling equations as,

$$\frac{\omega}{v}(s) = \frac{K_m/J \times L}{s^2 + \left(\frac{R}{L} + \frac{K_f}{J}\right) \times s + \frac{K_f \times R + K_m \times K_b}{J \times L}}$$

A. DC Motor Model

The plant transfer function obtained after parameter substitution as

$$\frac{\omega}{v}(s) = \frac{6150}{1.508 \times s^2 + 24.94 \times s + 48.612} \tag{5}$$

B. Feedback control system with uncertainty

The majority of feedback control problems can be cast into the Figure (Figure 2). In this form, the problem can include consideration of reference input, plant disturbances, and measurement noise. The plant is assumed fixed and known by the transfer function G(s), with a disturbance signal D(s). The Plant has an input U(s) or the control effort, and an output Y(s). The controller is known and fixed with a transfer function K(s). The output is subjected to measurement noise M(s), and the system has a reference signal R(s) which is to be followed by the plant output.

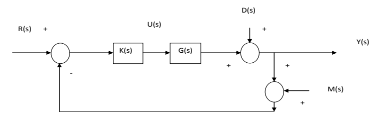

Figure 2. Standard feedback Configuration

C. Specifications

The specifications for the Controller are: Speed control range: 2000 to 8000 rpm, Rise time: under 0.5 second, Overshoot: less than 10%, settling time: under 1.0 second.

III. DESIGN OF CONTROLLER IN MATLAB

There are various algorithms to design a controller, out of these PID, LQG, LSDP are chosen for our purpose. PID controller is the most classical way to design a controller and its algorithm is simple also but it is unable to track parameter variation. Therefore when a plant is running with uncertainties, robustness in control can be included by adopting LQG and LSDP approaches. These methods design controller in such a way that it will able to track parameter variation up to certain limit but its time responses becomes somewhat sluggish than PID.

A. PID Controller

The PID controller was designed using Ziegler-Nichols open loop algorithm and preference has been given for set point tracking. The controller obtained is,

$$C(s) = 0.15689 \times \frac{(1 + 0.019s) \times (1 + 0.74s)}{s} \tag{6}$$

Its recorded Rise Time: 0.0765 s, Settling Time: 0.403s and Peak Percent Overshoot: 11%. Its response is given in Figure 3. The difference equation becomes,

$$u_k = u_{k-1} + 0.3e_k + 0.1e_{k-1} + 0.002e_{k-2} \tag{7}$$

B. LQG Synthesis

The LQG controller has been designed using the parameters as Robustness = 50%, Measurement Noise = 25% and desired Controller Order = 3. The controller obtained is,

$$C(s) = 0.72547 \times \frac{(1 + 0.021s) \times (1 + 0.99s)}{s \times \{1 + 0.00069s + (0.00048s)^2\}} \tag{8}$$

Its recorded Rise Time :0.019s, Settling Time: 0.0877s and Peak Percent Overshoot :13.2%. Figure 4 depicts Output Response versus time and Controller Effort versus time. The difference equation becomes,

$$u_k = u_{k-1} + 6.9 \times 10^{-4}u_{k-2} + 2.3 \times 10^{-7}u_{k-3}$$

$$+1.47e_k + 0.76e_{k-1} + 0.01e_{k-2} \tag{9}$$

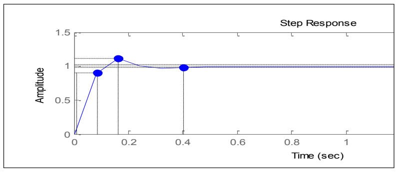

Figure 3. Output Amplitude vs. Time of PID

C. Loop Shaping Experiment I

The controller was designed using the parameters as Target Open-Loop Bandwidth = 10 and Desired Controller Order = 2. The controller obtained is,

$$C(s) = 0.078567 \times \frac{(1 - 2.4 \times 10^{-7}s) \times (1 + 0.51s)}{s \times (1 + 2 \times 10^{-9}s)} \quad (10)$$

Its recorded Rise Time was : 0.153s, Settling Time : 0.637s, Peak Percent Overshoot : 9.36%. Response of the compensated plant is shown in Figure 5. The difference equation becomes,

$$u_k = 0.9u_{k-1} - 1.9 \times 10^{-9}u_{k-2} + 1.5e_k$$

$$+0.5e_{k-1} - 1.2 \times 10^{-7}e_{k-2} \quad (11)$$

D. Loop Shaping Experiment II

As a second trial the controller was designed using the parameters as Target Open-Loop Bandwidth = 5 and Desired Controller Order = 1. The controller obtained was,

$$C(S) = 7.1071 \times 10^{12} \times \frac{1 + 0.51s}{1 + 9 \times 10^{13}s} \quad (12)$$

and it is approximated as,

$$C(S) = 7.107 \times \frac{1 + 0.51s}{90s} \quad (13)$$

Its Rise Time was noted as 0.153s, Settling Time as 0.632s and Peak Percent Overshoot as 9.36%. Response of the compensated plant is shown in Figure 6. The difference equation becomes,

$$u_k = 0.9u_{k-1} - 1.9 \times 10^{-9}u_{k-2} + 1.5e_k$$

$$+0.5e_{k-1} - 1.2 \times 10^{-7}e_{k-2} \quad (14)$$

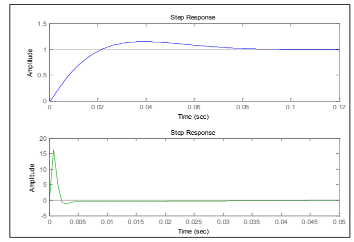

Figure 4. Output Response versus time and Controller Effort versus time of LQG

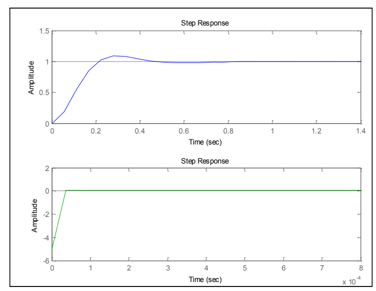

Figure 5. Output Response versus time and Controller Effort versus time of LSDP I

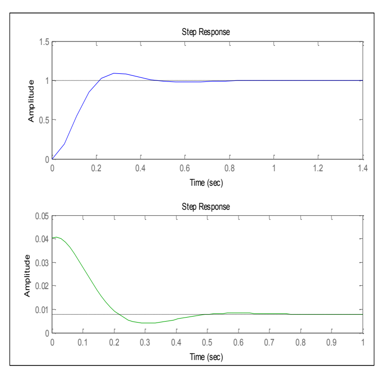

Figure 6. Output Response versus time and Controller Effort versus time of LSDP II

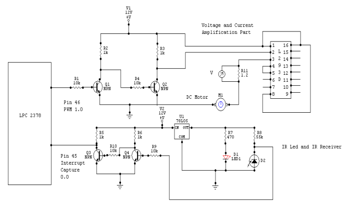

Figure 7. Schematic of the control circuit

IV. Embedded Controller Implementation on ARM

For controlling dc motor, the motor is connected to ARM based microcontroller (NXP LPC2378) through an interfacing circuit. Schematic of the whole arrangement is shown in Figure 7. For software part, three threads are running in parallel, one is for sensing set-point, another for calculating speed and third one for generating control effort. Flow chart of the control strategy is shown in figure 8. Programming has been done using C. Photograph of actual hardware setup is shown in figure 9 to 12.

V. Results and Discussion

A variety of experiments have been performed on each type controller with the varying set point to evaluate the performance. The programmed software has inbuilt capability to observe and store various important transient and steady state parameters. Several experiments have been performed but due to space constraints only important three results are summarized in Table I to IV. It is observed that rise time is somewhat greater than the estimated one. Rise time, estimated from simulation has been less than 100ms but practical result shows it above 1s. Overshoot and steady-state error are also more than estimation. Settling time has not been measured here, because it is taking more than 5 seconds and the settling band is also high. There is mismatch between the result of simulation and the practical implementation. This problem persists because at present the system lacks mechanism to supply negative control effort. Whenever the controller produces negative control effort, zero voltage is given to the motor. This would have improved the performance to desired level; our next research task aims at modifying the controller for supplying bi-directional control-effort.

VI. Conclusion

Speed control with precision and high speed of operations is important in Micromanufacturing applications. Underlying uncertainties in system parameters have been dealt by using a robust controller design. High precision control implementation requirements have been met on ARM board because

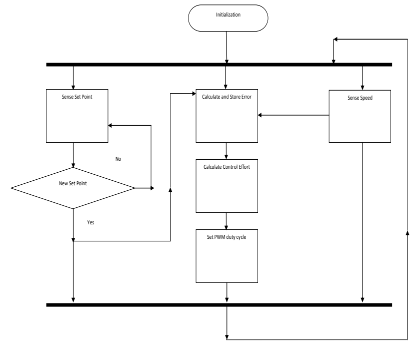

Figure 8. Control Strategy

Figure 9. PCB of interfacing Circuit

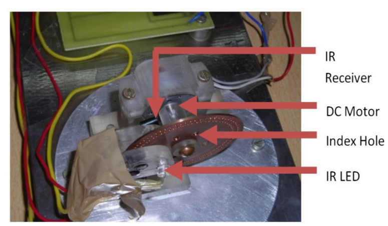

Figure 10. Motor and accessories for Measuring Speed

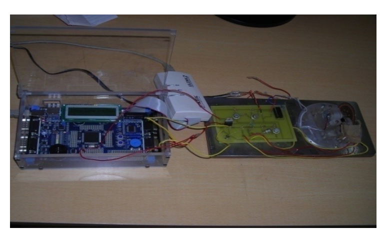

Figure 11. Complete Hardware Module

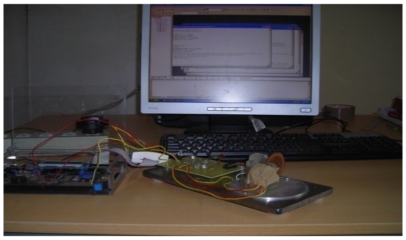

Figure 12. Hardware and Software Environment

Table I
RESULT FOR PID CONTROLLER AT SET POINT = 100 HZ

Rise Time (ms)	Peak Time (ms)	Peak Percent Overshoot (%)	Max Error (+/-) at steady state(%)
900	1400	8	15
900	1500	25	20
900	1200	15	10

Table II
RESULT FOR LQG CONTROLLER AT SET POINT = 100 HZ

Rise Time (ms)	Peak Time (ms)	Peak Percent Overshoot (%)	Max Error (+/-) at steady state(%)
300	1100	55	13
200	1000	50	20
600	900	50	12

Table III
RESULT FOR LSDP I CONTROLLER AT SET POINT = 100 HZ

Rise Time (ms)	Peak Time (ms)	Peak Percent Overshoot (%)	Max Error (+/-) at steady state(%)
200	600	52	12
300	500	15	10
300	700	45	15

Table IV
RESULT FOR LSDP II(APPROX.) CONTROLLER AT SET POINT = 100 HZ

Rise Time (ms)	Peak Time (ms)	Peak Percent Overshoot (%)	Max Error (+/-) at steady state(%)
1500	2000	20	17
1200	1900	5	12
1400	1900	2	13

it is 32-bit microcontroller; additionally it has all necessary facility for concurrent programming and real-time control for fast handling of events in Micromanufacturing applications.

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