REDUCING SETTLING TIME IN POSITIONING SYSTEMS USING AN IMPROVED ADAPTIVE IMPULSE CONTROL TECHNIQUE

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ABSTRACT

This paper focused on the design of an improved adaptive controller that reduces settling time in positioning systems – a system that adapts to actual relationship between pulse width and displacement, and nonlinear time variation in system models. The controller eliminates oscillatory transients and achieved fast settling time in comparison with proportional integral derivative (PID) control technique. The fast settling time is achieved with the combination of impulsive control and adaptive control that can adapt to the actual relationship between pulse width and displacement

Key words — Adaptive Control, Controller, Servomechanism, Settling Time

1. INTRODUCTION

In modern process control system, reducing settling time is paramount in achieving high precision in position control.

Settling time is the duration between the moment a new reference is applied and the moment the system output enters and stays within or equal to a specific tolerance of that reference.

Positioning entails the operation to move an element, such as machine tools like drill or cutter from a certain point in space to another target point with high efficiency and high precision. The principle of positioning is the control of speed in accordance with the position, performed to immediately eliminate the remaining distance to the target position.

Servomechanism is used for the speed control of a system and position an object by comparing position of the controlled system through a feedback signal. Servomechanism performance can be measured by "settling time", defined as the time from the arrival of a position command until the measured position reaches and stays within an acceptable distance from the target position (Answers.com, 2017).

The precision and speed at which the position of machine components can be controlled is subject to friction. That is, friction constitutes significant implications for servo control. Friction poses a challenge to precise control. Friction is the nemesis of precise control (Yang, 2004). Substantial literature on control report that friction in systems produces nonlinear dynamic effects, especially at slow velocities and when there is a reversal in the direction of motion (Rigney, Pao and Lawrence, 2007). Friction in servomechanism is very complicated and has significant influence on positioning (Rigney, 2008).

Precise positioning in spite of the large variations in friction near zero velocity requires a controller that can match or compensate for these and other friction (i.e. for a multi-faceted friction) behaviour. Many approaches exist to improving settling time in precision positioning machines. The known practical approaches may be divided into the following general categories: improving the physical hardware, improving conventional compensation techniques with or without a friction model (several of the techniques require an accurate friction model while some others do not require a friction model), and impulse control (Haessig and Frieland, 1991). It is understood in the technical publications that most of these techniques for improving compensation are based on methods for turning certain constants in the Proportional Integral Derivative (PID) controller transfer function, while some of the others are based on the modification of the PID controller (Kim, Chae, Jeon and Lee, 1996).

In this paper, Improved Adaptive Impulse Technique was used to achieve fast settling time in position control by designing a method for improving adaptive position controller that is based on the combination of impulsive control and adaptive control; which is capable of adapting to strong system non-linear, time-variation and friction model uncertainties.

Open –Loop Control Systems

An open-loop control system is designed to meet the desired goals by using a reference signal that drives the actuators that directly control the process output. Output feedback is not present in this type of system. Figure 1 shows the general structure of an open-loop control system.

Closed-Loop Control Systems

In closed-loop control systems the difference between the actual output and the desired output is fed back to the controller to meet the desired system output. Often this difference, known as the error signal, is amplified and fed into the controller. Figure 2 shows the general structure of a closed-loop feedback control system (Cliff and Southward, 1990).

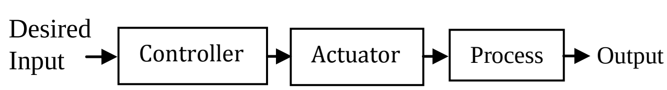

Fig. 1: *Open loop control system*

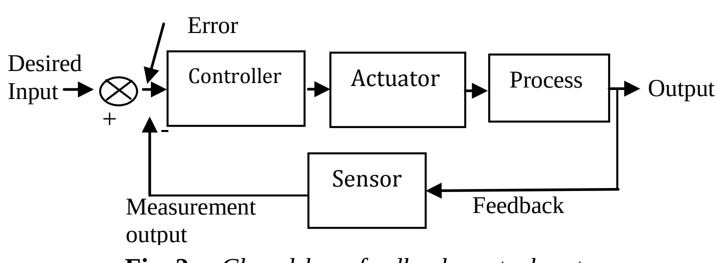

Fig. 2: *Closed-loop feedback control system*

2. DESIGN OF NEW METHOD FOR IMPROVING ADAPTIVE

The controller is composed of a main control loop, an adaptive control algorithm, pulse interpolation algorithm, pulse generator, and update algorithm. The figure 3 shows an overall diagram of the proposed improved adaptive position controller.

The proposed method for improving adaptive control technique is to quickly move positioning machines from one point to the next without losing the precision. The technique used in the design is based on the combination of impulsive and adaptive control.

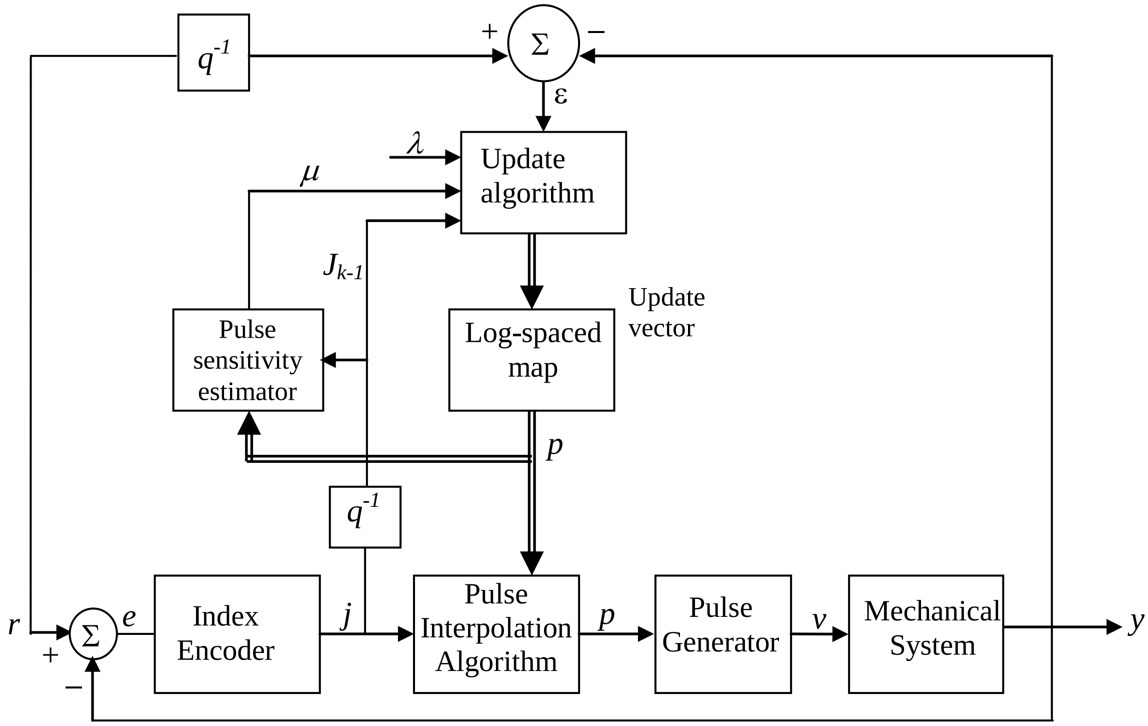

Fig. 3: *Block diagram of proposed improved adaptive controller*

The design uses impulse control which is the application of short pulses (forces) and the adaptation of the impulses (i.e. the applied pulses) by the dynamic online updates of control table (i.e control map composed of displacement vector and pulse vector) using interpolation algorithm. The controller automatically tunes a set of control parameters online. Each control parameter is a pulse value expected to produce a given displacement.

But small displacements have been produced with repeatability using impulsive control. The impulsive control approach can be simplified to the calculation of single pulse per positioning event without requiring the measurement or estimation of intra-pulse velocity or acceleration.

To control position over a wide range of displacement, pulses must be varied as a function of desired step size. The relationship between pulse duration and step size is a complex function.

The pulse value expected to cause each displacement is learned either by a short training exercise or by ongoing updates that progressively refine the parameter.

To apply pulses for displacements not stored in the control map, the nearest stored values are interpolated, and thereafter the interpolated pulse is applied. If the system does not move exactly by the desired displacement, an optional update is performed. The update attempts to correct only the specific pulse parameters that are used to interpolate the most recently applied pulse.

When the stored relationship converges to the actual relationship of the machine, each pulse applied to the system will be accurate. When each pulse is accurate, one or few pulses will be needed to reach each desired destination. When fewer pulses are needed, settling time is improved and efficiency is increased. This is because the control overhead will be reduced. Each machine operation with its associated control mechanics needs time and space, hence several of that will mean several units of time and space. So, the fewer the pulses the better the settling time is improved.

3. EXPERIMENTAL DESIGN

The control of a DC motor is used to evaluate the performance of the proposed adaptive controller. The assessment method used is to evaluate the response of the DC motor under a PID controller and its response under the proposed method for improving adaptive controller to see the improvement on the settling time.

This will be achieved by applying a step command to the DC motor system when under a PID controller and when under the proposed improved adaptive controller.

For the simulation study the DC motor position control experimental setup given on figure 4 is used. The controlled entity is the shaft position.

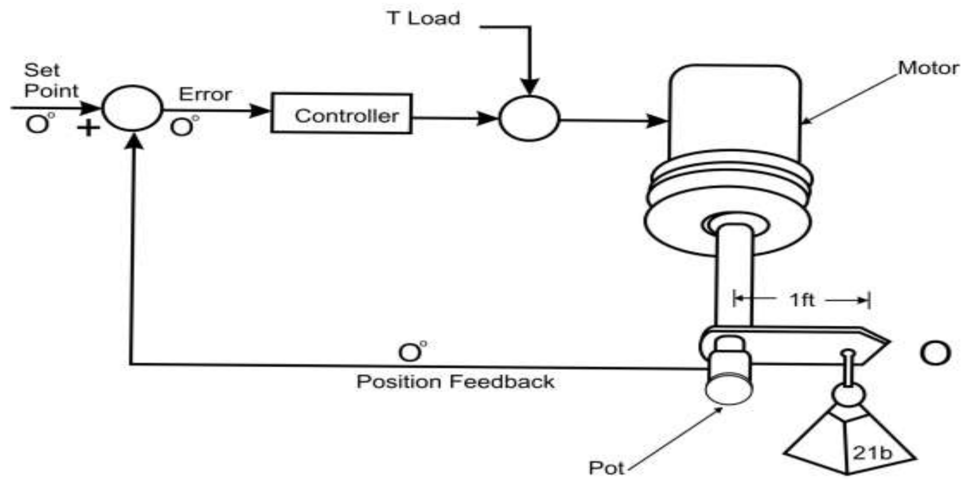

Fig. 4: *Schematic diagram of the experimental setup.*

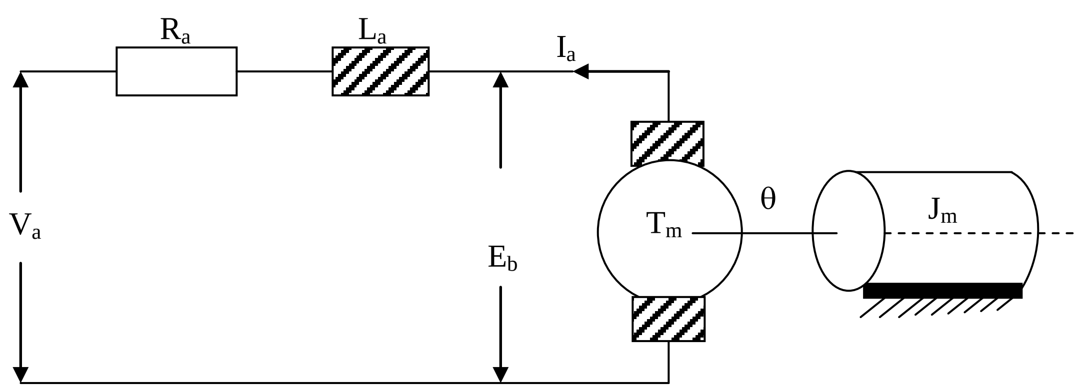

Fig. 5: *DC Motor model*

4. MATHEMATICAL MODEL OF THE EXPERIMENTAL SETUP

Figure 5, shows a separately excited DC motor equivalent model of the setup.

$$\text{Va(t)} = R_a . i_a(t) + L_a . \frac{di_a(t)}{dt} + e_b(t) \quad (1)$$

$$e_b(t) = K_b . \omega(t) \quad (2)$$

$$\text{Tm(t)} = K_T . i_a(t) \quad (3)$$

$$\text{Tm(t)} = J_m . \frac{d\omega(t)}{dt} + B_m . \omega(t) \quad (4)$$

Where V_a = armature voltage (V)

R_a = armature resistance (Ω)

L_a = armature inductance (H)

i_a = armature current (A)

e_b = back emf (V)

$\omega(t)$ = angular speed (rad/s).

NOTE: $\omega = \frac{d\theta_m}{dt} \omega$

T_m = motor torque (Nm)

θ = angular position of rotor shaft (rad)

J_m = rotor inertia (kgm^2)

B_m = Viscous friction coefficient (Nms/rad)

K_T = Torque constant (Nm/A)

K_b = back emf constant (Vs/rad)

Rearranging equation (1), (2), (3), & (4) and taking Laplace transform, the transfer function between shaft position and armature voltage at no-load is:

$$\frac{\theta(S)}{V_a(S)} = \frac{K_T}{L_a J_m S^3 + (R_a J_m + L_a B_m) S^3 + (K_T K_b + R_a B_m) S} \quad (5)$$

The performance of the improved adaptive controller is tested using PID as the benchmark. The proportional – integral – derivative (PID) control is a benchmark for almost every new control approach. Whatever new controller or technology is presented, its performance is almost always compared to PID.

Results achieved using PID model were examined. Then the result of applying the improved adaptive technique to control the test plant is examined. The goal here is to examine if settling time improves over the range of application of the step command.

The output position is taken as measured in encoder counts. (1 encoder count = 0.3927 milliradians, or $\frac{1}{16000}$ of a revolution).

For application where the load is to be rapidly accelerated or decelerated frequently, the electrical and mechanical time constants of the motor plays an important role. The mechanical time constants in these motors are reduced by reducing the rotor inertia.

Plant: A system to be controlled. For this simulation the plant is the system whose transfer function is given in equation (5).

The controller provides excitation for the plant, designed to control the overall system behaviour.

To model the plant, in the MATLAB M-file:

num = K_T;

den = $[(La*Jm).((Ra*Jm)+(La*Bm))((K_T*kb)+(Ra*Bm))]$

plant = tf (num, den)

tf = in built MATLAB transfer function

Another key MATLAB m-file required variable is the variable (contr) representing the PID parameter gains expressed thus:

Contr = *tf([k_d k_p K_i], [1 0]);*

Where,

K_d = derivative gain

K_p = proportional gain

K_i = integral gain

PID parameters were tuned based on the Ziegler-Nichols tuning method.

Simulation is carried out by comparing the performance of a test plant under the control of improved position controller with that under the control of proportional integral derivative (PID) controller.

For the simulation the DC motor position control experimental setup given in figure 4 is used. Table 1 show the DC motor specifications used in the simulation.

Table I: D.C motor specification (Datasheet4u, 2017)

Type	DC Motor
Moment of inertia of the motor	$1e^{-3}$
Rated motor voltage	6v (DC)
Armature inductance	0.01(H)
Armature Resistance	0.005(Ω)
Electromotive force constant	0.22
Back e.m.f constant	1.5
Damping ratio	1.91
Torque constant	0.061

5 THE PID RESPONSES

PID control creates a control signal from a linear combination of three terms: - the control error e(t), the integral of the error and the derivative of the error.

$$U(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \quad (6)$$

$$= K_P e(t) + \frac{1}{T_I} \int e(t)dt + T_D \frac{de(t)}{dt} \quad (7)$$

Where,
K_P = proportional gain,
K_I = integral gain, K_D = derivative gain,
T_I = integral time and T_D = derivative time.

PID controllers are usually tuned using hand-tuning or Ziegler – Nichols method.

6 TESTING WITH IMPRECISE MODEL

In this test an imprecise modeling of the DC motor is made with false parameters to study the response of the controllers (i.e. the PID and the improved adaptive controller). To this effect the following test manipulated parameters have been chosen according to table II.

With this imprecise plant model and the application of the same step command, the dynamic response of the system is shown and discussed.

Table II. Test Manipulated Parameters

Type	DC Motor
Moment of inertia of the rotor	$1e^{-1}$
Rated motor voltage	6v (DC)
Armature inductance	0.01(H)
Armature Resistance	0.05(Ω)
Electromotive force constant	0.22
Back e.m.f constant	1.5
Damping ratio of the mechanical system	10.91
Torque constant	0.061

7 THE IMPROVED ADAPTIVE CONTROLLER RESPONSES

In presenting the response of the improved adaptive controller, the same conditions used for the PID control test is used.

For the adaptive technique the following parameters are used:

Table III: Improved adaptive controller parameters.

Parameter	**Value**
Number of allowed pulse attempt	110
Pulse sensitivity	0.001
Learning constant	0.0043
Initial control table (i.e. training vector — training pulse and initial displacement)	
Pulse	**Displacement**
-1000000	-10000
-100000	-1000
-10000	-100
-1000	-10
-100	-1
0	0
100	1
1000	10
10000	100
100000	1000
1000000	10000

The pulse values are measured in microsecond and the displacement in encoder counts.

8 DATA ANALYSIS

The PID Responses

On Testing the PID with Precise Model (model that the parameters were not manipulated or tampered), the dynamic response of the system by the step command with reference to table "I" is as shown in figure 5. From the figure, it can be observed that the dynamic response output of the system converges within a tolerance (about 5% (0.05) of the reference command in 1.2 seconds. After the initial transient, however, the system begins to hunt about that tolerance of the reference. If tolerances of less than 0.05 are required in this instance, then the settling time which may actually be infinite, must be practically assigned a Not a Number (NaN) representation value or for the sake of convenience to the maximum time associated with the data window, which in this case is 2.00 seconds.

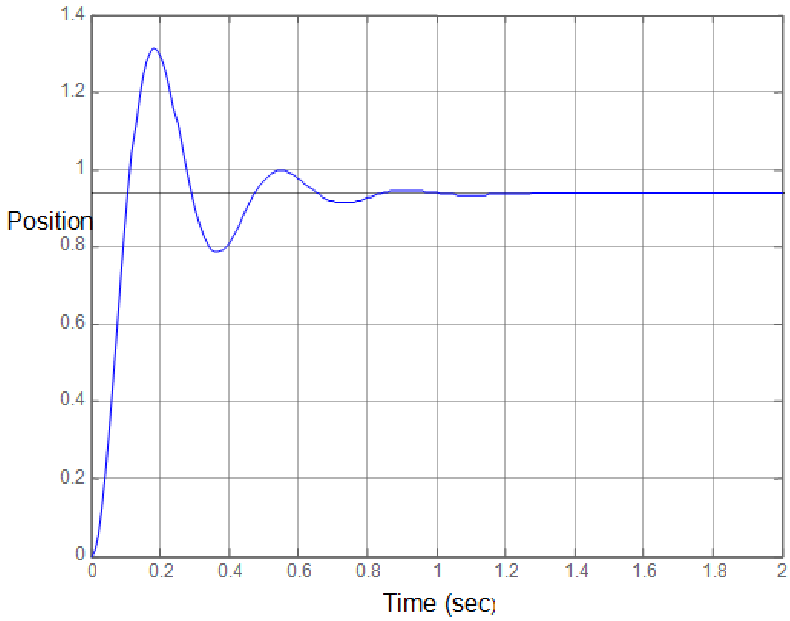

Fig. 5: *Step response with PID control*

The improved adaptive controller responses

The response of the improved adaptive controller to the step command based on the system parameter given in table “I” is shown in figure 6.

From the figure it can be seen that the system response produces no overshot, steady-state error is eliminated and the system achieved improved settling time at 0.4 seconds at almost a tolerance of zero. This is about 66.67% of the settling time saved when compared to PID response shown in figure 5.

Figure 7 gives the step response of the system using the imprecise plant model i.e. the model with manipulated or tampered parameters (the manipulated parameters are given on table II). Like in the previous step response it can be seen that the system shows no overshoot, no hunting eliminating steady state error, however at a little later settling time (0.5 seconds) at close to zero tolerance (i.e. high precision). Compared to the system response under PID control, this is a much better settling time (about 60% of the settling time saved).

Figure 8 gives the compared step response of the PID control with the improved adaptive control.

The results so far show that the improved adaptive controller has the potential to produce superior performance without sacrificing precision and Simulation studies conducted showed that the improved adaptive controller showed no overshoot. Even with imprecise plant model it is observed that the improved adaptive control technique can drive the system to target or at least close to zero error and at fast reduced settling time. The response of the Improved Adaptive Controller using imprecise plant model further shows that this new controller has every potential to save the cost and time being spent in friction model.

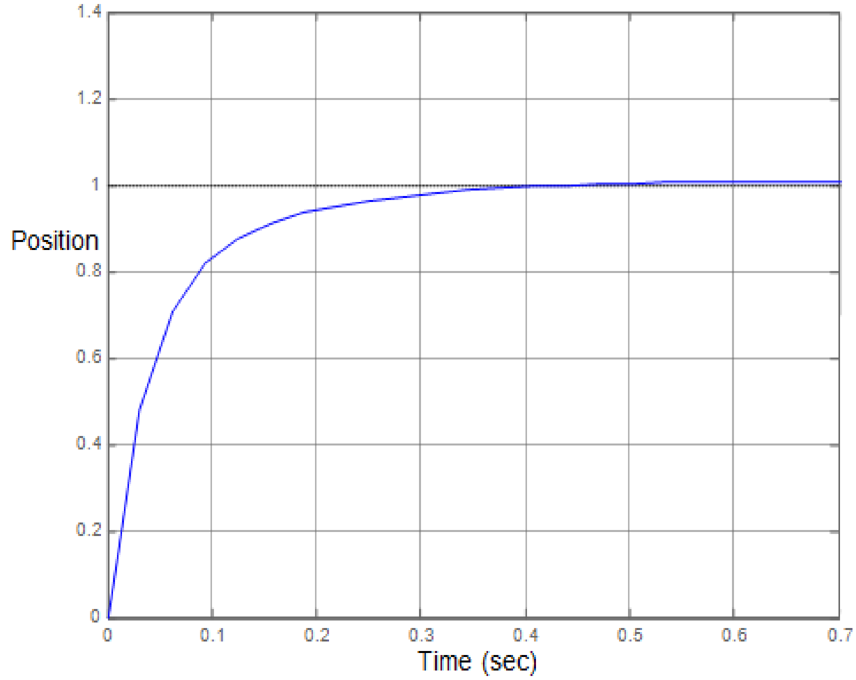

Fig. 6: *Improved Adaptive Control*

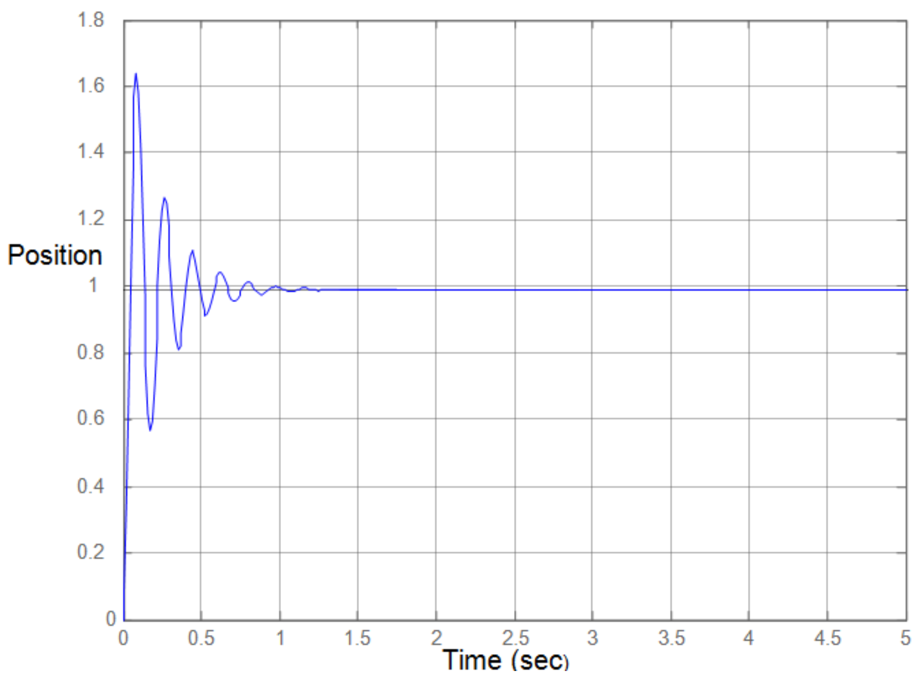

Fig. 7: *Step response with PID control with Imprecise Model.*

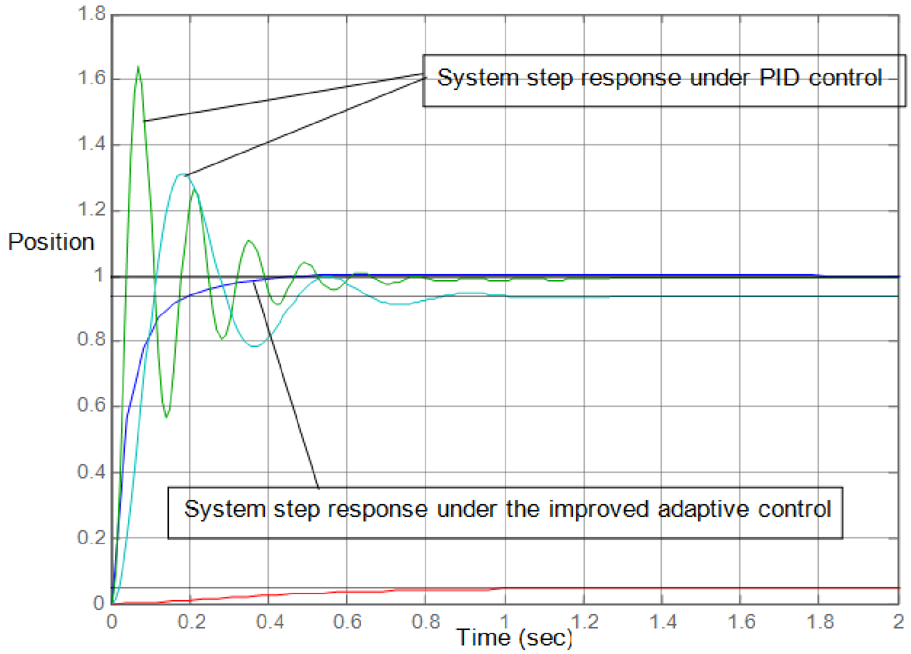

Fig 8: *Compared step response of the PID control with the improved adaptive control*

9. CONCLUSION

This paper focused on the problem of precision control in servo mechanisms in order to achieve reduced settling time. High precision in positioning control is vital in modern process control systems.

Minimizing settling time is desirable in many diverse applications, including automated manufacturing, where small settling time leads to reduced manufacturing time and cost; improvement of the machine efficiency generates immeasurable added value, including reduction of labour and the machine floor area for the same quantity of production.

Again, this new controller has the potential to eliminate the cost and time being spent in modelling friction because it works very well with imprecise model.

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