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Predictive Control of Axis Drift in Linear Motion Control Systems

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The positional accuracy of a linear motion system used in machine tools can be enhanced by using closed loop feedbackinvolving a positional measurement by means of an encoder.The position error is developed in the linear motion system because of the thermal expansion of the ball screw assembly and also due to the error in encoder measurement values. The traditional error compensation and correction methods used in a linear motion system do not satisfy all the dynamic performance requirements and constraints. In this paper, a Model Predictive Control (MPC) algorithm is proposed to reduce the position error of the linear motion control system at no-load and light load conditions. The future predictions made by the model predictive controller are based on the behaviour of the ball screw motion mechanism and encoder measurements to enhance the position accuracy of the linear motion system. The performance of the proposed model predictive controller is verified for no-load conditions in ball screw based linear motion system, and the results have been shown to outperform the current Proportional, Integral and Derivative (PID) and Fractional Order Proportional, Integral and Derivative(FOPID) control methods.

Keywords: Ball screw assembly, FOPID, Linear motion control system, MPC, PID controller

Introduction

The linear motion control has been widely used now a day due to the increasing demand for precision in the machining applications. The performance of the linear motion system has a great influence on the positional accuracy of the CNC Machining process. The main elements of a linear motion system are the servo drive and feed drive system. In the past few decades, the positional accuracy of the motion control system has been achieved by developing a semi-closed loop system, in which the motion of the feed drive is measured by the encoder. From the value of the encoder and the screw pitch, the motion control system calculates the position of the axis. The encoder measurement values are affected by various factors such as temperature, vibration, and humidity, which lead to the positional error values in the motion control system. It is also found that the error due to the thermal factor accounts for 70% of the total measurement error values of the encoder.[1] Also, when the ball screw drive system is running, lot of heat is generated as a result of which thermal expansion of the screw occurs which further induces the positional deviation of the linear motion control system.[2] Temperature induced positional deviation in ball screw drive system is compensated manually by adjusting the positional coordinates in the controller[3,4] and also by integrating shape memory alloys with feed drive system.[5]

The majority of the linear motion control systems used in machine tool applications operate on the PID control approach for automatic compensation of various positional errors that occur in feed drive system.[6] Yang *et al*. proposed a Proportional Integral (PI) based control loop for permanent magnet AC servo motor drives to enhance its dynamic performance.[7] PID controller is normally efficient and easy to implement, but has several drawbacks. By its design, it is a reactive type and thus it requires a high level of position error to achieve effective control results. Also, the tuning process involves a high degree of expertise and experience.[8,9] Fractional Order PID (FOPID) controllers can be used in linear motion control applications to deal with the change in system dynamics effectively, they still correct the error after its occurance.[10] Kumar *et al*. compared the tuning method of FOPID controller for field controlled DC servo motor using its physical model.[11]

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The following research gap is identified from the above literature survey: (i) the manual and mechanical compensation of axis drift in a linear motion control system is time-consuming and ineffective when system dynamics change. (ii) Lack of physical model of DC servo drive based linear motion control system for effective tuning of PID parameters. (iii) The PID and FOPID based automatic error correction methods used for servo drive systems correct the error only after its occurrence, and also they cannot handle the system dynamics and constraints effectively. The model predictive controller that predicts the required control action based on the system model is proposed in this work to enhance the positional accuracy of the linear motion control system.[12] The MPC control algorithm that uses the optimizer offers good performance against system error values due to temperature, vibration, and measurement disturbances of the linear motion systems.[13] The mathematical model required for the design of an MPC controller for a linear motion control system is formulated using the state space approach. This paper is organized as follows: first the state-space model of the linear motion control system consisting of a DC servo drive and a ball screw assembly is formulated, and then the MPC algorithm is designed using the state space model. The performance results of the MPC algorithm are compared and verified with the existing PID and FOPID controllers for the above model at no-load and light load conditions.

Experimental Details

DC Servo Motor with Rotational load

The mathematical modelling of DC servo motor along with the rotational load is done by changing the armature current, keeping field current constant. The electrical circuit of dc servo motor with mechanical load is shown in Fig. 1.

Now the air flux ϕ is proportional to the field current i_f of the motor is given by

$\phi \propto i_f$; $\phi = k_f i_f$

As the motor start speeding up, a back emf (e_b) is induced in the motor armature.The induced back emf is proportional to the motor speed (ω) and its direction is opposite to armature input voltage.

$e_b \propto \omega$

$$e_b = k_b \frac{d\theta}{dt} \quad \ldots (1)$$

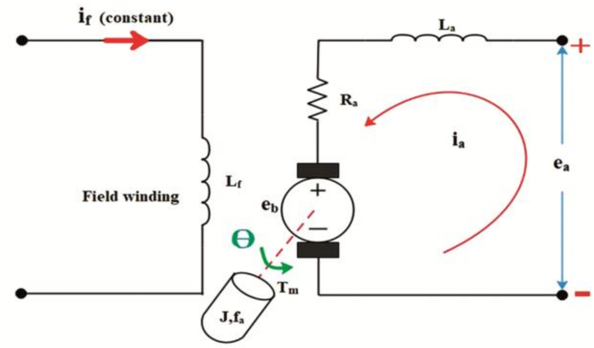

Fig. 1 — Electrical circuit for DC servo motor

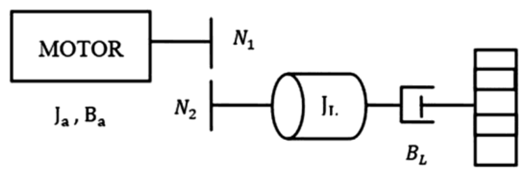

Fig. 2 — DC servo motor with rotational load

where, k_b is the back emf constant and $\frac{d\theta}{dt}$ is the angular velocity of the motor.

By applying Kirchhoff's voltage law for the armature circuit with rotational load, we get

$$e = i_a R_a + k_b \frac{d\theta}{dt} + L_a \frac{di}{dt}. \quad \ldots (2)$$

$$J \frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = T_m = K_t i_a \, . \quad \ldots (3)$$

By applying Laplace transform to the above Eqs (2) and (3), we get

$$\frac{\theta(s)}{V_a(s)} = \frac{k_1}{[J_m s^2 + B_m s][L_a s + R_a] + k_1 k_b s}. \quad \ldots (4)$$

Calculation of J_m and B_m

The mechanical constants J_m and B_m need to be specified in order to study about the DC servo motor connected with the ball screw assembly. The DC servo motor with inertia J_a and damping B_a in the armature rotates the mechanical load of inertia J_L and damping B_L is given in Fig. 2. By Knowing the gear box relationship, N_1 and N_2, the inertia J_L and damping B_L of the load, the mechanical constants J_m and B_m is calculated as follows.

$$J_m = J_a + J_L\left(\frac{N_1}{N_2}\right)^2; \; B_m = B_a + B_L\left(\frac{N_1}{N_2}\right)^2 \quad \ldots (5)$$

Relation Between Angular and Linear Displacement

The servomotor rotation is converted in to a linear motion in a ball screw assembly using the relation given in Fig. 3.

L represents the step of the lead; β represents the lead angle of the ball-screw; and *x(t)* represents the linear advance in the linear motion control system.[14] In this way

$$X = \frac{L}{2\pi}(\theta). \quad \ldots (6)$$

where, θ represents the angular movement produced by the DC Servo motor, given in radians.

From the Eq. (6) we get,

$$\theta = \frac{2\pi}{L}(X). \quad \ldots (7)$$

The component $\frac{2\pi}{L}$ can be replaced by a variable P, so that the Eq. (7) becomes

$$\theta = P(X).$$

Replacing Eq. (7) in Eq. (4) and applying Laplace transform we get,

$$\frac{X(s)}{V_a(s)} = \frac{k_1}{[P[J_m s^2 + B_m s][L_a s + R_a] + k_1 k_b s]} \quad \ldots (8)$$

The Eq. (8) can be converted into a state space models as follows; the state variables are selected for position (θ), speed (ω) and the armature current (i_a) as

$x_1 = \theta,\ x_2 = \omega, x_3 = i_a$ and then the state space model is written as

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -B_m/J_m & (P * K_t)/J_m \\ 0 & -K_b/(P * L_a) & -R_a/L_a \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1/L_a \end{bmatrix} e \quad \ldots (9)$$

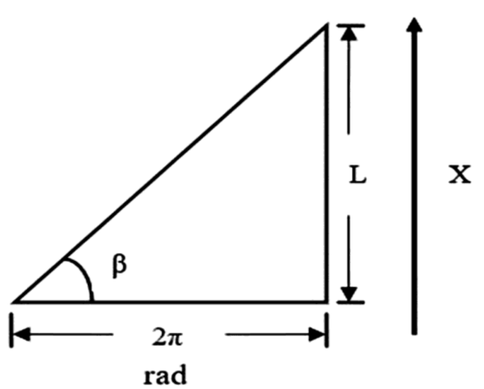

Fig. 3 — Relation between angular and linear displacement

$$Y = [1 \quad 0 \quad 0] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad \ldots (10)$$

PID based Ball Screw Motion System

The PID controller is a control loop feedback mechanism that is conventionally used in various industrial control applications.PID controllers are prominently used in motion control applications for the position control of linear motion control systems. The PID controller involves the calculation of constant parameters such as Proportional (P), Integral (I), Derivative (D) that represent the present, the past and the future error. A PID controller corrects the error which is the difference between a desired set point and a measured encoder value by setting the gain values of k_p, T_i, T_D. The gain values are needed to be carefully tuned in order to achieve the optimum position accuracy using this controller. The schematic block diagram of the PID controller is shown in Fig. 4. The linear motion control system consists of DC servo motor and Ball screw assembly which is modelled through state space approach and is connected with PID controller to form a closed loop system**.**

The Simulink model of the PID controller of the linear motion control system is given in Fig. 5. Here the state space model of the ball screw assembly and PID controller is developed using the Simulink block. The step signal is given as the input to the system model as a target value and the output of the plant model is given as the residuals to the PID controller to form a closed loop system and then the tuned controller output is fed as the input to the system model. The optimal PID gain values of k_p=0.01, T_i =0.02 µs, T_D=0.02 µs are generated by auto tuning the PID controller for the given transfer function of the linear motion control system.[15]

FOPID based Ball Screw Motion Control System

The PID controller performance can be improved by incorporating fractional order derivative and integral action into an existing PID controller, often known as the FO-PID controller.[16] Along with the

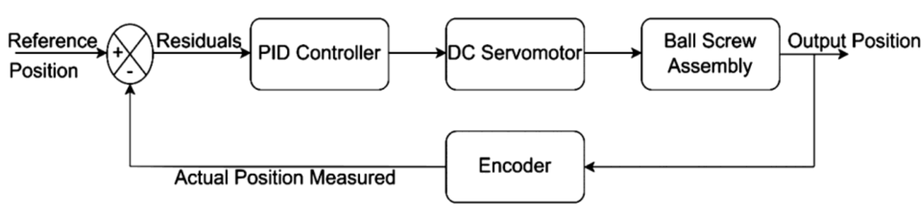

Fig. 4 — PID controller block diagram

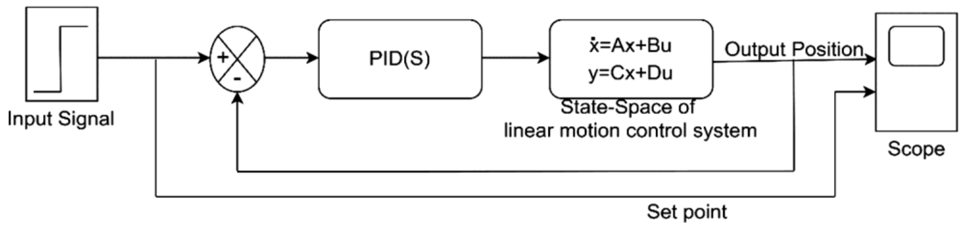

Fig. 5 — Simulink model of PID controller

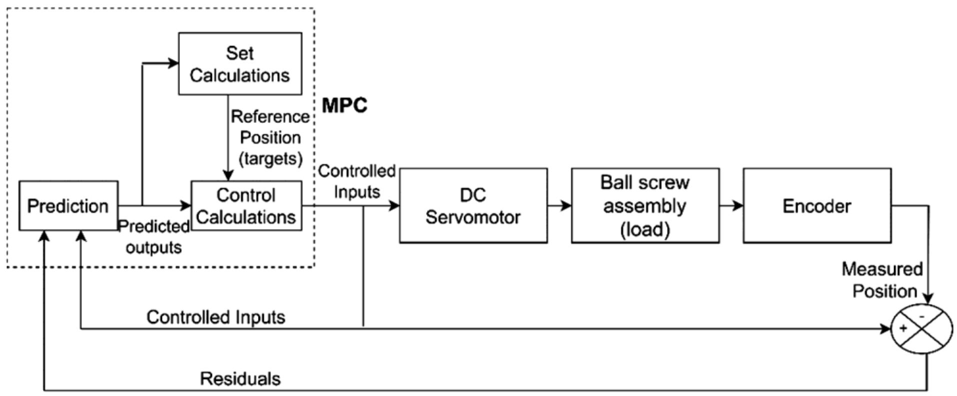

Fig. 6 — Block diagram of MPC

proportional (K_p), derivative (K_d), and integral (K_i) constants, the FOPID controller also uses two additional parameters termed fractional integration λ and fractional derivative μ. Integral (I) and Derivative (D) actions in a FOPID controller typically have a fractional order and have a range of 0 to 2. The FOPID controller performs better than the conventional PID controller for the systems with higher order, long time delay and with a nonlinear disturbance.[17] This controller provides better output performance and robustness against model uncertainties, load disturbances and high frequency noise by enabling the optimal tuning of its five parameters.[18]

MPC Design for Ball Screw Motion Control System

The MPC is a digital control algorithm originally designed in the mid-1970s for the process control industries. It is a model based control algorithm that uses system model and feedback measurement to predict future control. MPC predicts the system's output over a time period using the system model based on the controller's estimation of future output sequences.[19] An effective control sequence is then obtained by minimizing a quadratic cost function to reduce the positional error of the linear motion controlsystem.[20] The components of control horizon signals are applied to the linear motion control system at each sampling interval in order to allow regular updating of new positional values.[21] The MPC algorithm performs two calculations, such as the set point calculations and the control action calculations. The set point is the reference point or the target value of the plant to be reached. The block diagram of the MPC is given in Fig. 6, in which the plant model is the DC servomotor connected with the ball screw assembly. The first control element will be taken into account and it will be repeated after each iteration. Then the value of the prediction and control horizon, sample time and constraints values are to be set for the plant model to have fine-tuned performance of the linear motion control system.

The MPC algorithm uses the optimizer to reduce the error between the set position value and the actual measured value from the encoder. The optimizer generates the optimal trajectory based on the system constraints. The graphical representation of the MPC calculations is clearly represented in Fig. 7. Model Predictive Control algorithm is developed based on a mathematical model of the system. The state space model of the linear motion system is used as a model in the model predictive control system design.

The current information required for future prediction is described by the state variable at the current time using the state space model.

$$x_m(K+1) = A_m x_m(K) + B_m u(k) \quad \ldots (11)$$

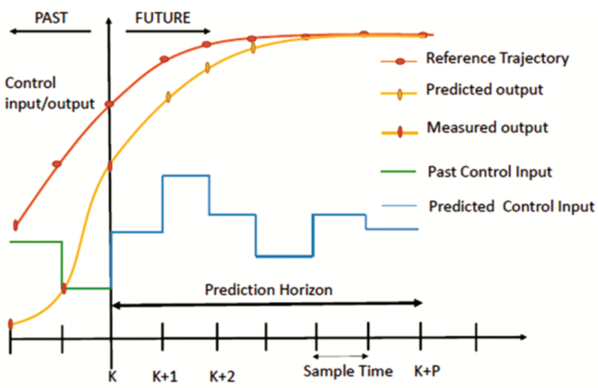

Fig. 7 — Graphical representation of MPC

$$y(k) = C_m x_m(K) \quad \ldots(12)$$

where, u(k) is the input or manipulated variable; y is the Linear motion system output; and x_m is the state variable vector with the dimension of n_1. The state-space model consists of the input signal u(k) to the output y(k) can be represented as

$$y(k) = C_m x_m(K) + D_m u(K) \quad \ldots(13)$$

However, because of the receding horizon control principle, where current plant information is needed for prediction and control, we implicitly presumed that the input u(k) could not influence the output y(k) at the same time. Thus, $D_m = 0$ in the plant model.

$$\overbrace{\begin{bmatrix} \Delta x_m(K+1) \\ y(K+1) \end{bmatrix}}^{x(K+1)} = \overbrace{\begin{bmatrix} A_m & 0_m{}^T \\ C_m A_m & 1 \end{bmatrix}}^{A} \overbrace{\begin{bmatrix} \Delta x_m(K) \\ y(K) \end{bmatrix}}^{x(K)} + \overbrace{\begin{bmatrix} B_m \\ C_m B_m \end{bmatrix}}^{B} \Delta u(K) \quad \ldots(14)$$

$$y(k) = \begin{bmatrix} 0_m & 1 \end{bmatrix} \begin{bmatrix} \Delta x_m(K) \\ y(K) \end{bmatrix} \quad \ldots(15)$$

where, $0_m = 0_m = [\overbrace{0\ 0\ \ldots.\ 0}^{n_1}]$.

The variables triplet A_m, B_m and C_m represent the augmented model of the system. This model is mainly used in predictive controller design.

Replacing the Eqs (9) and (10) in the form of Eqs (14) and (15), we get

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -B_m/J_m & (P * K_t)/J_m \\ 0 & -K_b/(P * L_a) & -R_a/L_a \end{bmatrix};$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 1/L_a \end{bmatrix}; C = [1 \quad 0 \quad 0]; D = [0].$$

Table 1 — Parameters of Linear motion control system

Parameter	Definition	Values
B_a	Motor damping constant [Nms/rad]	0.01
B_L	Load Damping constant [Nms/rad]	1
B_m	Equivalent viscous friction coefficient [Nms/rad]	0.02
J_a	Motor inertial constant [Kgm^2]	0.02
J_L	Load inertial constant [Kgm^2]	1
J_m	Equivalent moment of inertia [Kgm^2]	0.03
K_t	Motor torque constant [Nm/A]	0.5
K_b	Back emf constant [Vs/rad]	0.5
R_a	Motor armature resistance [Ω]	8
L_a	Motor armature resistance [H]	0.45
L	Lead of the screw (mm)	1
N_1,N_2	Gear teeth (respectively)	25,250

The modelling parameters of the DC servo motor based ball screw assembly for the linear motion control system are chosen and the values with its units are displayed in the Table 1.

Substituting the parameter values of Linear motion control system consisting of DC servomotor and ball screw assembly in the above A, B, C, D matrices, the resultant matrices become:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -0.67 & 104670 \\ 0 & -1.76E-4 & -17.78 \end{bmatrix};$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 2.22 \end{bmatrix}; C = [1 \quad 0 \quad 0]; D = [0].$$

Through the repeated predictions and the control actions (x(k)), the error of the system is completely reduced effectively.[22] The model predictive controller can be designed in MATLAB software by means of an MPC toolbox. It is a collection of tools that enable us to design, analyze and implement advanced control system algorithms. It provides a Graphical User Interface (GUI) that enables the user to work in a convenient manner. The Simulink model of the MPC controller is given in Fig. 8. The plant model is imported in to the MPC controller block by setting the necessary horizon values and constraints in the MPC designer of the MATLAB toolbox. The plant model is given as the state space block of the Simulink model and then the output of the plant model is fed as the residuals to the controller block so that the output from the controller tunes the system as a repeated

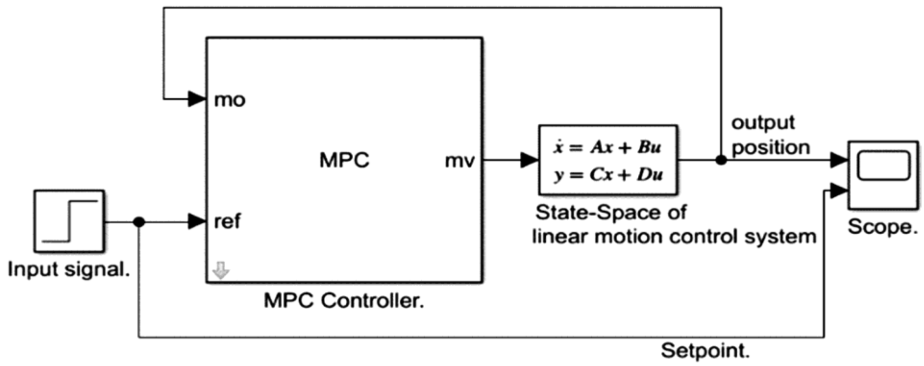

Fig. 8 — Simulink model of MPC controller

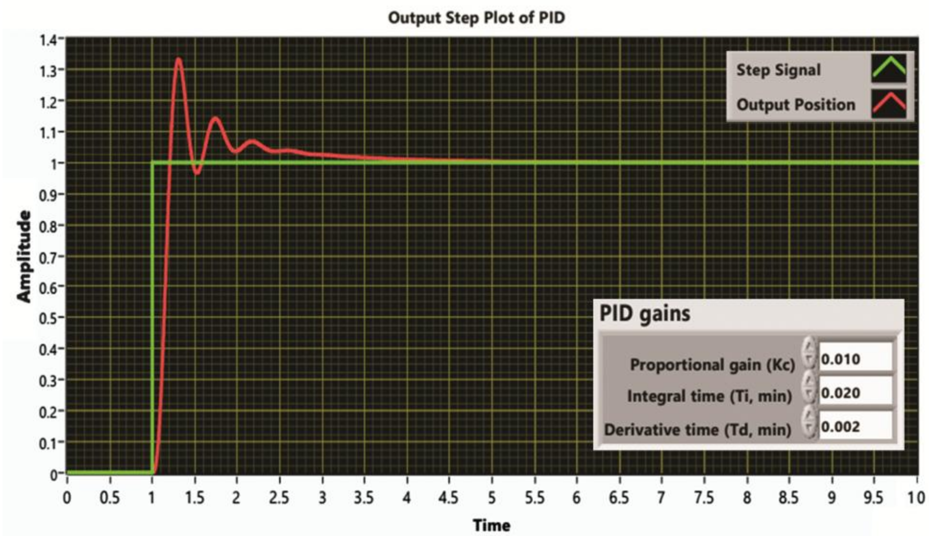

Fig. 9 — Front panel of PID in Lab VIEW

iteration of operation until the system reaches the given input reference signal values. Here, the input voltage signal is given as the step signal and the output positional values were obtained and compared with the reference signal in scope.

PID and MPC Design in Lab VIEW

The position control of a linear motion control system using a MPC is implemented in LabVIEW using a state space approach. In this method, the state space model representing the system is imported using control and simulation loops to predict the system behavior, and then the state space model is again created to implement the action of the controller. This predictive capability makes the MPC method more appropriate for precise position control applications. In this the r(k) represents the reference signal which is the step input and u(k) represents the manipulated variable which is the controllable variable based on the system feedback(y(k)). The design of PID and MPC algorithms in lab view will enhance their implementation using CRIO hardware. The LabVIEW provides the user interface with the help of the control and indicators which form the basic components of the LabVIEW application. The PID and MPC control is created with the help of the control and simulation tool in which the reference signal is step input and then the transfer function representing the system is developed and the output positional value of the system is given as feedback, and is compared with reference to check for an error.[23]

The front panel of the PID based position control in LabVIEW is shown in Fig. 9. The user interface allows the user to tune the gain values of the PID controller to have optimum output response from the linear motion system. The PID gain values and the output response of the PID controller are presented in Fig. 9.

The front panel of the position control of linear motion control system with the MPC controller[24] is given in Fig. 10. In this MPC control design, the controller parameters, the Prediction and the control horizon values are taken as 10 and 2 respectively. The set point profile for the reference signal is also shown in the front panel. The simulation loop and then the graph representing the output positional value and the control action response are also shown in the front panel of the MPC design in LabVIEW. The MPC controller can be successfully implemented in the linear motion system used in axes drive of the CNC machines for better position tracking.[25,26]

Results and Discussion

The MPC and PID controller of the linear motion control system was developed and the output of the controllers are discussed as follows, the output response of the linear motion system in the form of Simulink waveform using PID controller is shown in Fig. 11. In which the yellow line represents the input step signal which is given as the input to the system, the red line represents the corresponding linear positional output.

We can clearly see that the PID controlled motion system has a high settling time and has more overshoot value as given in Fig. 11. Since the PID controller is a reactive type in nature, it predicts the error only after it's occurrence in the system. The output time domain step response of the FOPID controller based linear motion system is given in Fig.12.

The FOPID controller is implemented using ninteger tool kit in Matlab.[27,28] The tuning parameters are set as follows: K_P=0.000482, K_I=0.0001718, K_D=0.00021, λ= −0.5, μ=0.05. The step response of the FOPID controller is better than that of the PID controller in terms of peak overshoot, rise time and settling time. The Simulink waveform of MPC based linear motion control system is shown in Fig. 13. From the Figs 11,12 and 13, we can clearly

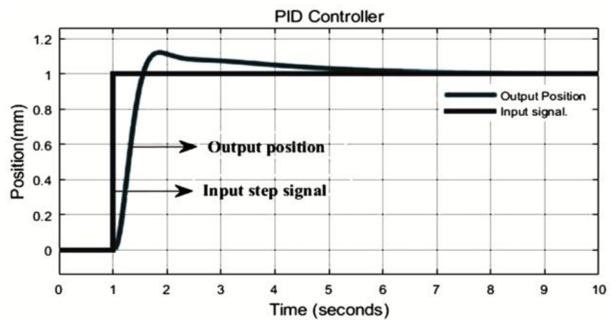

Fig. 11 — Step response of PID controller

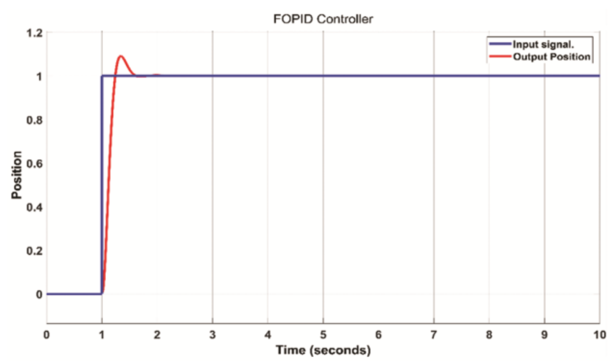

Fig. 12 — Step response of FOPID controller

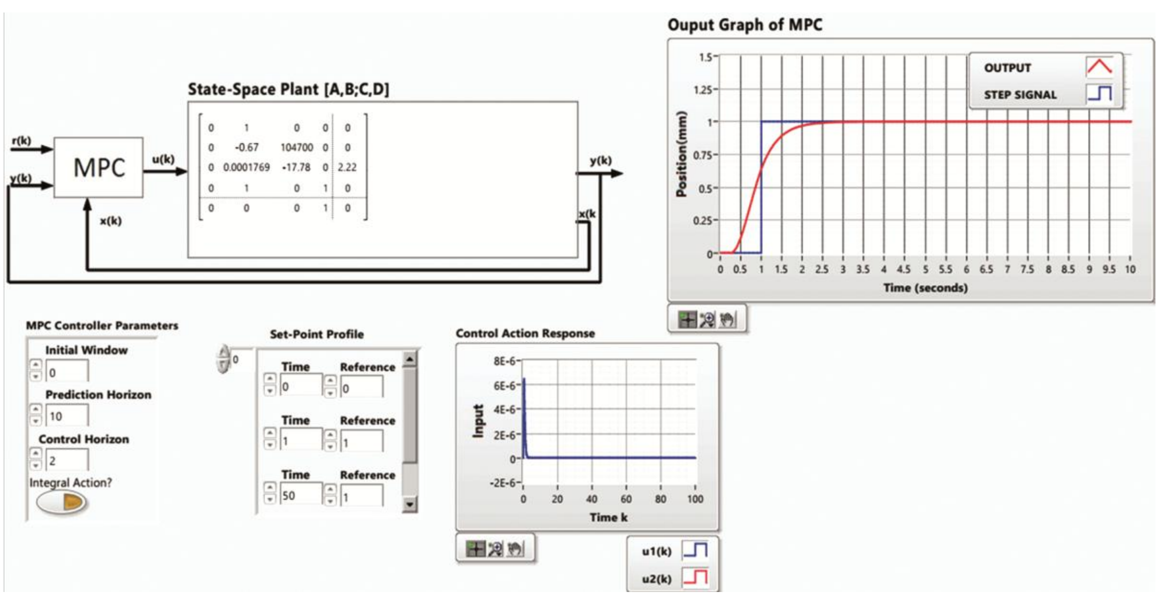

Fig. 10 — Front panel of MPC in Lab VIEW

observe that the MPC controlled system has very less overshoot value than PID and FOPID, since the MPC controller is a proactive type in nature it predicts the error in earlier manner and then it take necessary control action during each iteration of operation so it reduces the occurrence of error in the system as a results of which the MPC controller has the ability to correct error due to encoder measurement and position deviation due to vibration and temperature in linear motion system. The MPC and PID controller of the linear motion control system was developed through state space model and implemented in LabVIEW platform. This implementation helps in realize the above model in CRIO hardware.

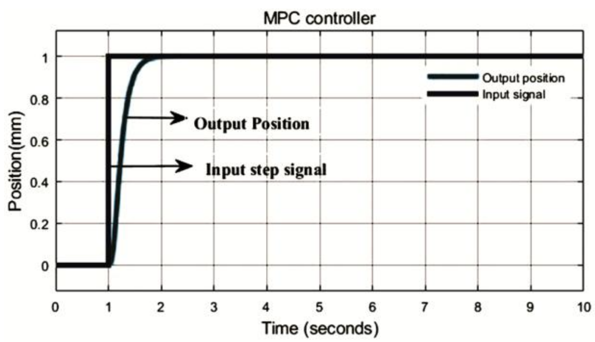

Fig. 13 — Step response of MPC controller

The simulated results obtained through output graphs are discussed as follows; the output linear positional values of the system using PID controller in the form of waveform in LabVIEW are shown in Fig. 14. In which the blue line represents the input step signal which is given as the input signal to the system, then the red line represents the corresponding linear positional values. From the Fig. 14 we can clearly see that the PID controlled system has the high settling time and has more overshoot value, since the PID controller is a reactive type in nature it predicts the error only after it's occurrence in the system.

The closed loop response of the MPC controlled linear motion control system as a waveform in LabVIEW is given in Fig. 15. In which the blue line

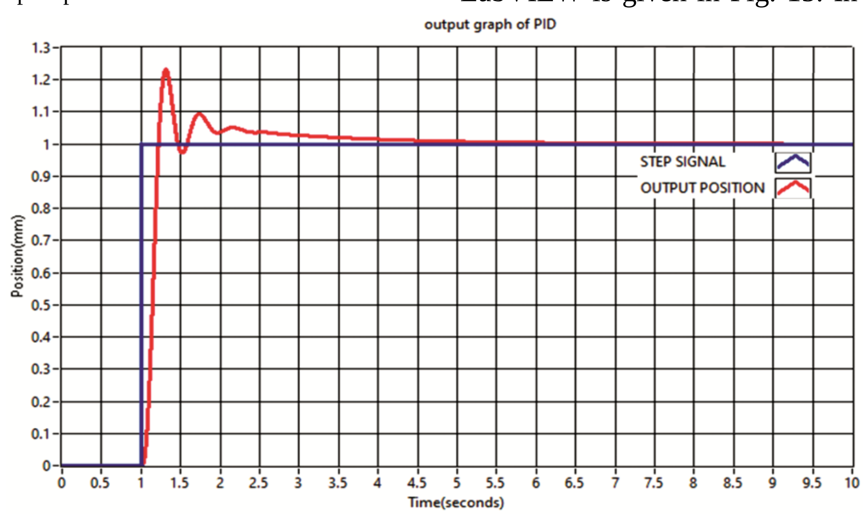

Fig. 14 —Step response of PID in Lab VIEW

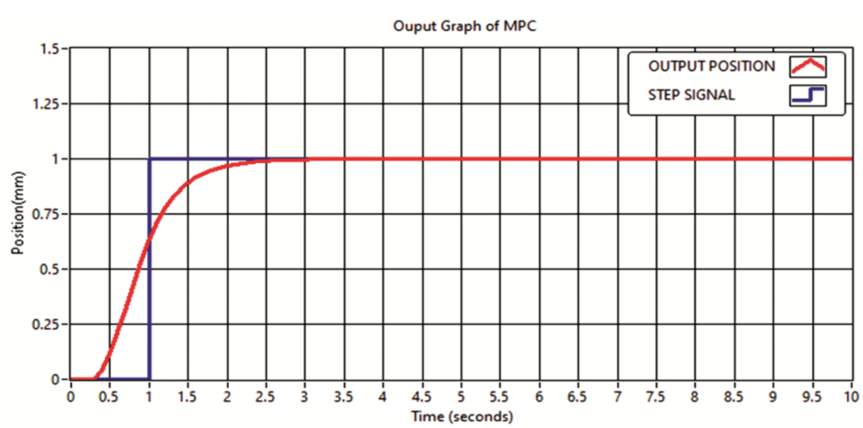

Fig. 15 —Step response of MPC in Lab VIEW

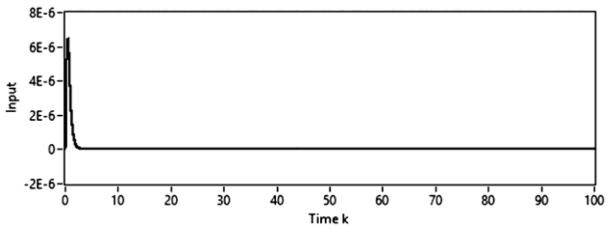

Fig. 16 — Control action response of MPC in Lab VIEW

Table 2 — Comparison between PID, FOPID and MPC

Parameters	PID	FOPID	MPC
Rise time (seconds)	1.248	0.158	0.374
Settling time (seconds)	4.54	1.53	1.71
Overshoot (%)	20.125	9.09	0.04
Steady state error	0.0088	0.0042	0.0005

represents the step signal which is given as input to the system, the red line represents the corresponding linear positional values. The control action response graph of MPC algorithm is shown in Fig.16.

We can clearly observe that the MPC controlled system has the low settling time and has less overshoot value than PID from the Figs 14 and 15, and also the MPC controller has lower damping ratio than the PID controller. Since the MPC controller is a proactive in nature and it predicts the error in predictive manner[29] and applies necessary control actions during each iteration of operation so it reduces the occurrence of error in the system as a results of which the MPC controller has high performance value when compared it with the PID controller.

Further comparison between PID, FOPID and MPC is shown in Table 2. It is concluded that the existing PID control method in linear motion control system has settling time of 4.54 (sec) while MPC system has low setting time 2.78 (sec) hence it is inferred that MPC has faster response than PID controller. The overshoot value of the PID is 20.125% whereas the MPC has 0.04% overshoot. This shows that the MPC provides smoother response of the system when compared with the PID control method. Root mean square error value in PID system is 0.1248 while MPC system has low error value of 0.0881, which shows that MPC controller gives higher accuracy compared to PID controller. Though FOPID controller provides better time domain results than PID controller, its peak overshoot is higher than the MPC controller. As an overall result, the use of Model Predictive Control algorithm in linear motion control system provides a better optimal control output response and system stability than the conventional PID control algorithm.

Conclusions

The Simulation results show that the FOPID controller provides better optimal control performance output than traditional PID controller for the varying dynamics of the system. But, the Model Predictive Controller, due to its predictive capability could be able to correct the error due to deviation in encoder measurement and system errors due to vibration and temperature effects and to achieve better performance in the linear motion system. The simulation and validation results show that MPC provides faster, smoother and more accurate results compared to the PID controller and hence can be successfully implemented in linear motion control systems for better tracking and performance results. In this work, the performance of the linear motion system using PID, FOPID and MPC controllers for no-load conditions is considered. The performance of the linear motion system for different load conditions will be taken as a future work by using adaptive PID controller and gain scheduling MPC controller.

References

1 Hu F, Chen X, Cai N, Lin Y J, Zhang F & Wang H, Error analysis and compensation of an optical linear encoder, *IET Sci Meas Technol*, **12** (2018) 561–566.

2 Shi H, Ma C,Yang J, Zhao L, Mei X & Gong G, Investigation into effect of thermal expansion on thermally induced error of ball screw feed drive system of precision machine tools, *Int J Mach Tools Manuf*,**97** (2015) 60–71.

3 Liu K, Chen F, Zhu T, Wu Y & Sun M, Compensation for spindles axial thermal growth based on temperature variation on vertical machine tools, *Adv Mech Eng*,**8** (2016) 1–10.

4 Li Y, Zhang J, Su D, Zhou C & Zhao W, Experiment-based thermal behavior research about the feed drive system with linear scale, *Adv Mech Eng*,**10(11)** (2018) 1–10.

5 Sosa I N, Bucht A, Junker T, Pagel K & Drossel W G, Novel compensation of axial thermal expansion in ball screw drives, *Prod Eng Res Devel*, **8** (2014) 397–406.

6 Dong X, Jian-qu Z & Feng W, Fuzzy PID control to feed servo system of CNC machine tool, *Procedia Eng*,**29** (2012) 2853–2858.

7 Yang S M & Lin K W, Automatic control loop tuning for permanent-magnet ac servo motor drives, *IEEE Trans Ind Electron*,**63(3)** (2016) 1499–1506.

8 Cuong N H, Nguyen T T & Thang T V, Fuzzy-PID-based improvement controller for CNC feed servo system, IHCI, (2020) 38–46.

9 Stephens M A, Manzie C & Good M C, Model predictive control for reference tracking on an industrial machine tool servo drive, *IEEE Trans Industr Inform*, **9** (2013) 808–816.

10 Tepljakov A, Alagoz A,Yeroglu C & Gonzalez E A, Towards industrialization of FOPID controllers: A survey on milestones of fractional-order control and pathways for future developments, *IEEE Access*, **9** (2021) 21016–21042.

11 Kumar P, Chatterjee S, Shah D, Saha U K & Chatterjee S, On comparison of tuning method of FOPID controller for controlling field controlled DC servo motor, *Cogent Eng*, **4 (1)** (2017).
12 Schwenzer M, Ay M, Bergs T & Abel D, Review on model predictive control: an engineering perspective, *Int J Adv Manuf Technol*, **117** (2021) 1327–1349.
13 Wang Y & Boyd S, Fast model predictive control using online optimization, *IEEE Trans Control Syst Techno*l, **18** (2010) 267–278.
14 Ruiz-Rojas E D, Vazquez-Gonzalez J L, Alejos-Palomares R, Escudero-Uribe A Z & Mendoza-Vázquez J R, Mathematical model of a linear electric actuator with prosthesis applications,*Proc18th Int Conf Electron, Commun Comput(Conielecomp)*(IEEE) 2008, 182–186.
15 Vikhe P, Punjabi N & Kadu C B, DC Motor speed control using PID controller in lab view, *Int J Innov Sci Mod Eng*, **3** (2015) 38–41
16 Khubalkar S W, Junghare A S , Aware M V, Chopade A S & Das S, Demonstrative fractional order PID controller based DC motor driveon digital platform, *ISA Trans*, **82** (2018) 79–93.
17 Shah P & Agashe S , Review of fractional PID controller, *Mechatronics*, **38** (2016) 29–41.
18 Monje C A,Vinagre B M,Feliu V & Chen Y Q, Tuning and auto-tuning of fractional order controllers for industry applications, *Control Eng Pract*, **16(7)** (2008) 798–812.
19 Maciejowski J M, *Predictive control with constraints* (Prentice Hall, HarlowU.K) 2002.
20 Xie Y, Liu Z,Li K,Liu J,Zhang Y, Dan D,Wu C,Wang P & Wang X, An improved intelligent model predictive controller for cooling system of electric vehicle, *Appl Therm Eng*, **182** (2021)1359–4311.
21 Wang L, *Model predictive control system design and implementation using MATLAB* (Springer-London) 2019.
22 Balaji V, Study of model predictive control using NI LabVIEW, *Int J Adv Res Sci Eng Technol*, **3**(2012) 257–266
23 Liu J, Zhang P & Wang F, Real-Time DC servo motor position control by PID Controller using LabVIEW, *Int Conf Intell Human-Machine Syst Cybernet(IHMSC)*(IEEE) August 2009, 206–209.
24 Derouiche M L, Bouallègue S, Haggège J & Sandou G, Rapid model predictive control prototyping with LabVIEW/CDSim and CompactRIO target, *4th Int Conf Control Eng Informat Technol (CEIT)* (Hammamet, Tunisia) December 2016.
25 Ramesh H, Xavier S A E & Kumar S B, Multiple model filter based position tracking in CNC machines,*Int Conf Signal Process Commun Netw*(*ICSCN)*(IEEE) 16–18 March 2017.
26 Xie Y, Özdemir D & Herfs W, Object-oriented modelling of machine tool feed axes: An approach to analysis of control parameters, *ProcInt Conf Ind Mechatron Autom* (IEEE) 2015, 1332–1337.
27 Tepljakov A, Alagoz B B, Yeroglu C, Gonzalez E, Nia S H H & Petlenkov E, FOPID controllers and their industrial applications: A survey of recent results, *3rd IFAC Conference on Advances in Proportional-Integral-Derivative Control (IFAC-PID)* (Ghent, Belgium),09-11 May2018.
28 Jamil A A, Tu W F, Ali S W, Terriche Y & Guerrero J M, Fractional-Order PID controllers for temperature control: A review, *Energies***15(10)** (2022) 1–28.
29 Pattanaik B, Sundaram B B, Mishra M K,Thirumoorthy D & Rastogi U, Industrial speed control of {IM} based model predictive controller using zeta converter, *J Phys Conf Ser*, **1964(6)** (2021) 1742–6596