



Control of Linear Electric Actuator with Hybrid Fuzzy PID Controller

Okan Uyar

Department of Mechatronic Engineering, Selçuk University, Turkey

Abstract

In this study, the actuator, which converts circular motion to linear motion, is controlled with a smart hybrid controller. The model includes the analysis of electrical and mechanical parts. The controller, on the other hand, has a design methodology that cleverly blends classical PID (Proportional Integral Derivative) and fuzzy controllers. In this design methodology, classical PID and fuzzy controller have an error parameter dependent blending mechanism. In order to compare the performance of the hybrid controller, the coefficients of the classical PI and PID controllers were obtained by tuning and the coefficients with the best response were used. For performance comparison of conventional controllers and hybrid controllers; rise time, settling time, maximum overshoot and common performance indices values are used. The hybrid controller showed higher performance in terms of maximum overshoot, settling time, rising time and performance indices. The potential benefits of using a hybrid controller for the control of linear electric actuators were demonstrated by the fact that it performed better than conventional PID controllers on the majority of evaluation criteria.

Keywords: fuzzy logic, hybrid controller, linear motor, performance indexes, speed and position control

1. Introduction

A linear electric actuator is a device that uses electricity to generate linear (straight-line) motion. Linear electric actuators work by converting electrical energy into mechanical energy. The conversion is done through the use of an electric motor. The motor is connected to a lead screw, which is turned when the motor is energized. The lead screw converts the rotary motion of the motor into linear motion, which moves the actuator body along its length. Electric actuators are used in a variety of applications, including automotive, aerospace, and industrial (Ustun, O., & Tuncay, R. N., 2006).

There are many benefits to using linear electric actuators over other types of actuators, such as hydraulic or pneumatic actuators. Electric actuators are more efficient than hydraulic or pneumatic actuators because they do not rely on fluid power to generate motion. This means that electric actuators can be powered by renewable energy sources, such as solar or wind power. Additionally, electric actuators are more precise than hydraulic or pneumatic actuators and can be easily controlled using electronics (Shao, K. et al., 2019).

The control of linear electric actuators is crucial in industrial and commercial applications as it guarantees their proper functioning and accuracy. The traditional control methods for linear electric actuators consist of Proportional-Integral-Derivative (PID) controllers and fuzzy logic controllers (FLC). However, the use of these controllers separately may not always result in optimal performance, particularly when the system dynamics are nonlinear and uncertain. A hybrid fuzzy PID controller is a solution that combines the advantages of both FLC and PID controllers, providing better overall performance (Nazemian, H., & Masih-Tehrani, M., 2020).

A fuzzy controller uses fuzzy logic to process information and make decisions, allowing for approximate conclusions to be drawn even with incomplete or uncertain data. These controllers are commonly used in systems with nonlinear characteristics, such as those in robotics and aerospace. While they can also handle linear systems, they may not have any specific advantage over other controllers in such cases. One key advantage of fuzzy controllers is their capability to handle multiple inputs and outputs simultaneously, leading to more accurate control of the system. However, these controllers can be slower and more complex than other types of controllers, making them harder to understand and debug (Rawat, A., & Azeem, M. F., 2020).

A hybrid fuzzy PID controller for linear electric actuators is composed of two main parts: the fuzzy logic controller and the PID controller. The fuzzy logic controller handles the nonlinear and uncertain dynamics of the system, while the PID controller fine-tunes the system's performance based on the feedback. The combination of these two controllers provides more robust and precise control of the linear electric actuator compared to using either controller alone (Anitha, T. et al., 2019).

The switching and blending mechanism are crucial in the hybrid control structure. Initially, it selects which controller's output will have a dominant influence on the control signal. The error value, which is normalized between -1 and 1, is used to calculate the weight multiplier, a coefficient. The outputs of the blending mechanism ("out1" and "out2" outputs in the Matlab function block) take the expressions $f(e)$ and $1-f(e)$. The fuzzy controller should be selected to minimize overshoot, while the PID controller should be chosen with parameters that provide a reasonable overshoot but a fast response. This way, the fast

response of the PID controller at the beginning and the low overshoot value of the fuzzy controller can be blended (Erenoglu et al., 2006).

These are just a few examples of the many studies that have been conducted on the control of linear electric actuators. In general, these studies have shown that the use of advanced control methods such as fuzzy logic and hybrid controllers can lead to improved performance compared to traditional PID controllers. Discrete-time fractional-order sliding mode control (SMC) is proposed to ensure desired performance in a linear motor control system by (Sun et al., 2018) theoretical analysis of the tracking error is also presented, and the method is validated through numerical simulations and experiments on a linear motor platform. (Yao & Xu, 2002) suggested a discontinuous projection-based ARC controller and the adaptive robust control (ARC) strategy. To approximate periodic nonlinear forces, design models with known basis functions and unidentified weights are used. The impact of various parametric uncertainties, such as inertia and motor parameters, is then minimized by using on-line parameter adaptation. According to a study by (Li & Wikander, 2004), servo problems can be reduced to straightforward regulator problems using a model reference discrete-time sliding mode control. To account for unknown disturbances, such as friction, it employs a one-step delayed disturbance approximation. The effectiveness of friction compensation is also examined in the study's analysis of the impact of sampling period selection. In a work from (Alter & Tsao, 1996) examines the designing for high stiffness and closed-loop tracking performance can be done via optimal H control. First, just position feedback is taken into account, and then cutting force feedback is added to increase closed loop stiffness. When compared to proportional-derivative control, stiffness can be increased by up to 46% with optimal position feedback. The benefits of using an accelerometer for precise motion control are examined by (Shim et al., 1998). The output of the accelerometer offers a separate measurement of the motion and could be a more reliable source of disturbance data than the position encoder. This extra measurement is useful for real-time control as well as modeling and system identification. The accelerometer is proposed as a novel controller structure for minimal-time point-to-point control. It is described by (Sendaula et al., 2004) how to control a hybrid linear actuator for a flush deck hatch of the CV/CVN type using a stochastic linearizing controller. The controller only needs to be aware of the hatch's position and speed. Studies in simulations demonstrate that the hybrid linear actuator is able to produce the necessary force to drive the hatch. For the high-speed and high-precision control of a linear motor positioner, a robust recursive sliding mode controller coupled with an adaptive disturbance observer (RSM-ADO) is proposed by (Shao et al., 2021). The benefit of the suggested ADO is that it can be designed without requiring knowledge of the disturbance's and its derivative's upper bound. In light of this, the ADO is ideal for rejecting all time-varying disturbances. The kinematic and dynamic model of a linear electric actuator to be used in elbow prosthesis to mimic the capacity of a muscle to extend and contract in a linear fashion is presented by (Ruiz-Rojas et al., 2008).

The aim of this research is to investigate the control of linear electric actuators using a hybrid fuzzy PID controller. The objective is to implement the controller for a linear electric actuator and evaluate its performance compared to traditional PID controllers. The results of this study will provide insights into the potential benefits of a hybrid fuzzy PID controller for controlling linear electric actuators and may have implications for similar industrial and commercial applications.

2. Modelling of electromechanical system

The linear electric actuator is an electromechanical system that comprises an electric motor, gearbox, and ball screw. In modeling the system, backlash, other gear losses, and torsional effects on the shafts are typically neglected. A representative equivalent of the electromechanical system is illustrated in Figure 1. The model includes the electrical components of the DC motor and the mechanical parts, such as the gearbox and ball-screw mechanism, along with their related frictions and inertias.

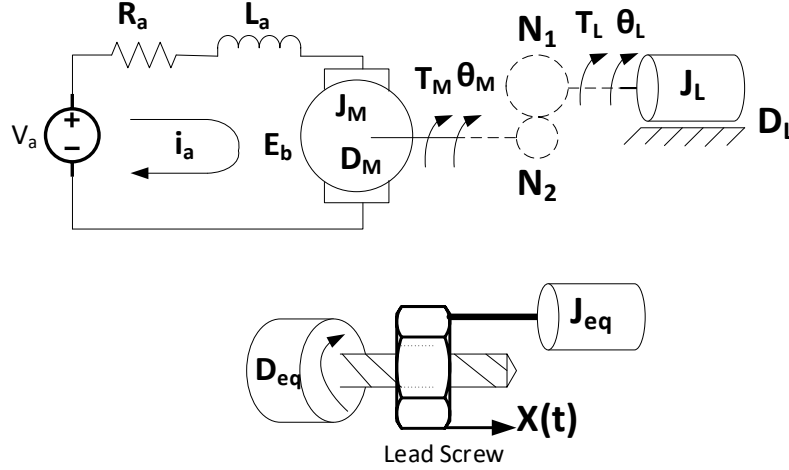


Figure 1: Principal model of linear electric actuator

The following mesh equations can be used to deduce the relationship between the armature current $i_a(t)$, the applied voltage $V_a(t)$, and the electromotive force $E_b(t)$:

$$R_a i_a(t) + L_a \frac{di_a(t)}{dt} + E_b(t) = V_a(t) \quad (1)$$

When there is a change in magnetic flux linked to a coil, an electromotive force (EMF) is induced. The magnitude of the EMF is directly proportional to the rate of change of the magnetic flux. It is the displacement of the motor windings per unit time, i.e., the angular velocity, that produces the change in the magnetic field in the motor. Therefore, the EMF value can be expressed as follows:

$$E_b(t) = K_b \frac{d\theta_m(t)}{dt} \quad (2)$$

Where K_b is the back e.m.f. constant, θ_m is the angular displacement of the armature windings.

The magnetic field of the air gap exerts a force on each conductor in a rotor. These current carrying conductors are positioned at a common radius from the rotor's center. As a result, each rotor's circumference produces torque, which causes the rotor to begin rotating. In summary, motor torque is related with the current in the rotor conductor. So we can write the following equation for expressing the torque with a torque constant K_t :

$$T_m(t) = K_t i_a(t) \quad (3)$$

We can express the equation, which can be obtained with the free body diagram of the mechanical components seen on the shaft side of the motor, as follows:

$$J_{eq} \frac{d^2 \theta_m(t)}{dt^2} + D_{eq} \frac{d \theta_m(t)}{dt} = K_t i_a(t) \quad (4)$$

Where;

$$J_{eq} = J_M + J_L \left(\frac{N_2}{N_1} \right)^2 ; D_{eq} = D_M + D_L \left(\frac{N_2}{N_1} \right)^2 \quad (5)$$

If we take the Laplace transform of the expression in equation (4) and leave the current i_a alone, we get the following equation:

$$\frac{1}{K_t} (s^2 J_{eq} + s D_{eq}) \theta_m(s) = I_a(s) \quad (6)$$

if we take the Laplace transform of the equation (1) and then replacing the armature current with equation (6), we find the following equation:

$$(R_a + L_a s) \frac{1}{K_t} (s^2 J_{eq} + s D_{eq}) \theta_m(s) + K_b s \theta_m(s) = V_a(s) \quad (7)$$

The transfer function of the system without ball-screw transformation is can be found as follows:

$$\frac{\theta_m(s)}{V_a(s)} = \frac{K_t}{(R_a + L_a s)(s^2 J_{eq} + s D_{eq}) + K_t K_b s} \quad (8)$$

The relationship between the angular feed caused by the motor and the linear feed after the ball screw can be given as follows in Laplace domain, where l represents the lead's pitch and $x(t)$ the linear feed:

$$\theta_m(s) = \frac{2\pi}{l} X(s) \quad (9)$$

Equations (8) and (9) are combined to obtain the final transfer function for the whole system:

$$\frac{X(s)}{V_a(s)} = \frac{l K_t}{2\pi [(R_a + L_a s)(s^2 J_{eq} + s D_{eq}) + K_t K_b s]} \quad (10)$$

The parameters selected for the simulation of the system model presented by Equation (10) are given in Table 1.

Table 1: System parameters for the simulation

Parameters	Values
l	0.03 m
K_t	0.0637 Nm/A
K_b	0.0640 V/(rad/s)
R_a	2.5 Ohm
L_a	0.0015 Henry
J_{eq}	2.5×10^{-5} kgm ²
D_{eq}	1.2×10^{-8} Nm/(rad/s)
N_1/N_2	6

3. Simulation results

The model created in Matlab/Simulink environment for the simulation of the system is given in Figure 2. There are classical PI and PID controllers and Hybrid Fuzzy PID controllers in the same simulation file.

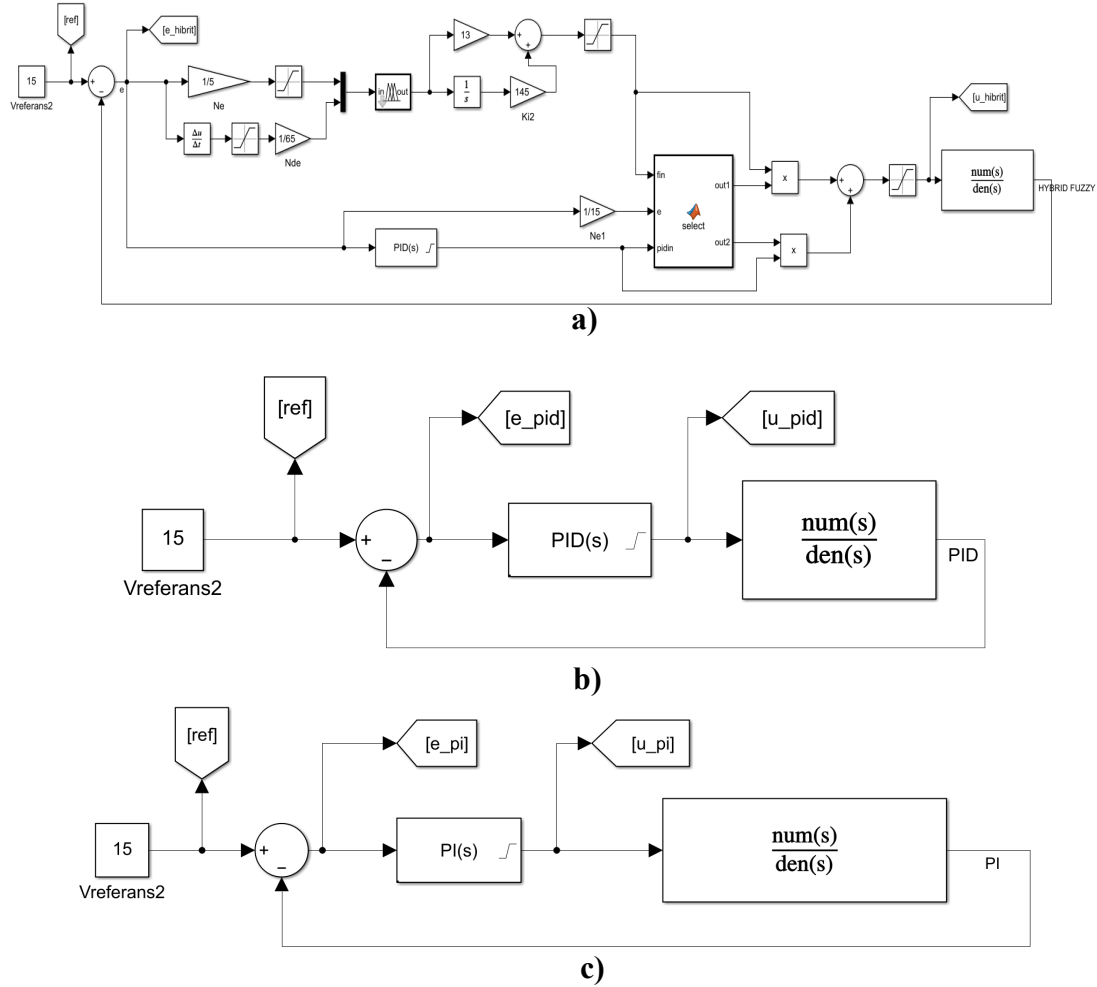


Figure 2: a) Hybrid Fuzzy PID Controller Structure, b) PID Controller, c) PI Controller

Time domain features are presented in Table 2 to compare the performances of the controllers. Step responses of systems with different controllers are given in Figure 3. It has been observed that the PI controller gives the best result in terms of maximum overshoot. On the other hand, it is seen that the hybrid controller gives better results in the rise time and settling time parameters.

The success of the controllers was also examined in terms of error-based performance metrics and the results are given in Table 3. Each of these criteria is a function of the error profile of the system output in terms of time. In most control system studies, these values are used as objective functions and are tried to be minimized. The performance criteria used in this work are summarized below.

The error signal $e(t)$ in a control system is given by

$$e(t) = r(t) - c(t) \quad (11)$$

where, $r(t)$ = input or reference signal, $c(t)$ = output signal

Performance Indices are as follows:

1. Integral Absolute Error (IAE)

$$IAE = \int_0^{\infty} |e(t)| dt \quad (12)$$

2. Integral time Absolute Error (ITAE)

$$ITAE = \int_0^{\infty} t|e(t)|dt \quad (13)$$

3. Integral Square Error (ISE)

$$ISE = \int_0^{\infty} e^2(t)dt \quad (14)$$

4. Integral time Squared Error (ITSE)

$$ITSE = \int_0^{\infty} te^2(t)dt \quad (15)$$

Table 2: Time responses of controllers

Controller	Rise Time	Settling Time	Over shoot
Hybrid	0.2222	1.1457	5.0095
PID	0.2775	1.6461	5.8567
PI	0.9509	1.3240	1.0115

Table 3: Performans indexes of controllers

Controller	IAE	ITAE	ISE	ITSE
Hybrid	0.2895	0.2421	0.1223	0.0182
PID	0.3446	0.3160	0.1389	0.0278
PI	1.1573	1.3091	1.1915	0.2937

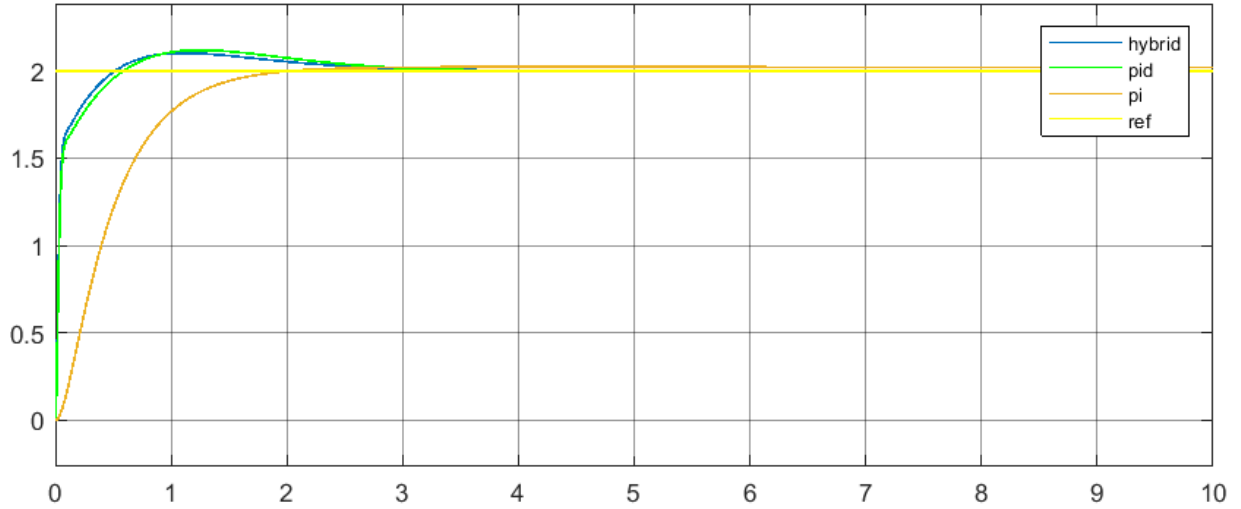


Figure 3: Responses of the systems with different controllers

4. Conclusion

In conclusion, this study presents the design and implementation of a smart hybrid controller for a linear electric actuator. The actuator, which converts circular motion to linear motion, was controlled using a hybrid controller that blends classical PID and fuzzy controllers. The hybrid controller design methodology includes an error parameter-dependent blending mechanism. The performance of the hybrid controller was compared to that of traditional PID controllers using various evaluation criteria such as rise time, settling time, maximum overshoot, and IAE and ITAE values. The comparison results showed that the hybrid controller outperformed traditional PID controllers on most evaluation criteria, demonstrating the potential advantages of using a hybrid controller for the control of linear electric actuators. These results provide insights into the potential benefits of using advanced control methods such as hybrid controllers for the control of linear electric actuators in industrial and commercial applications.

Other studies summarized in the introduction commonly have focused on the position control of the linear motor. Since the performance evaluations obtained in our study were not made in the studies that performed speed control, one-to-one comparisons were not made.

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