# PERFORMANCE ANALYSIS OF AN OPTIMIZED ROBUST CONTROLLER BASED ON TRACKING ERROR AND CONTROL EFFORT

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## ABSTRACT

Commonly, outcome of the end product in industry depends on the trajectory tracking performance of the machine. Concerning positioning or trajectory tracking, the endorsement of the control system to compensate the common drawback in most physical system is required. Thus, in this paper, three different control approaches are proposed and implemented in the Electro-Hydraulic Actuator (EHA) system. As a benchmark of the control system, the Proportional-Integral-Derivative (PID) controller is initially designed. Followed by the designs of an enhanced version of the PID controller, known as Fractional-Order (FO-PID) controller. Lastly, the designs of the robust Sliding Mode Controller (SMC) is carried out. Subsequently, the performance evaluation, particularly in trajectory tracking and controller effort are performed. To comprehensively analyse the output response, the data are extracted by using the popular performance indices including Root Mean Square Error (RMSE), Integral Square Error (ISE), Integral Time Square Error (ITSE), Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE). In the past study, most of these indices are applied to analyse the error generated from the system. In this paper, all the performance indices are performed not only to the system error but including the energy consumption of each controller. It is observed in the results, based on the performance indices in terms of error and voltage, the SMC capable of generating better outcomes with reference to tracking capabilities and energy usage.

**Keywords:** multi-trajectory tracking, electro-hydraulic actuator (EHA), robust control, sliding mode control (SMC).

## 1. INTRODUCTION

Control system is instrumental in realistic. It is demanding in industrial machinery including Electro-Hydraulic Actuator (EHA) system that is inherently nonlinear with various uncertainties in real-time [1]. Apart from energy efficiency, precision is produced through a control system. It was common knowledge that precision is one of the most important factors in production. Commonly, the EHA system involved a lot in clamping or shaping of the product, which required high force and precision. Imprecise motion can lead to damage and waste, which concurrently cause a financial loss.

Attributable to the fact that EHA system is commonly confronted with the nonlinear and uncertain characteristics, the mathematical representation can hardly imitate the physical system of the EHA in the real-world [2]. Generally, the resources of the nonlinearities including the compressibility of the oil due to the working temperature, the internal and external friction of the cylinder, the fluid flow characteristic in valve and cylinder [3]. Whereas the common uncertainties can be divided into two main types, including parametric uncertainties and uncertain nonlinearities [4]. For that reason, the control system is emerging to compensating these matters. However, the control system is challenging to be designed due to these existing issues.

For years, the industry preferred control approach, which is the widely known Proportional-Integral-Derivative (PID) controller has been usually performed in the EHA system [5-6]. By virtue of practical and user-friendly advantages, this controller has also become a subject of interest that extensively explored by researchers and academia. One of the common methods that often seen in the literature is the modification in terms of the controller's structure. For example, the fractional order control and the gain scheduling control that have been generally integrated with the PID controller [7-8]. These methods are proven to have more efficient performance compared with the traditional PID controller.
Regarding the robustness performance, the prominent Sliding Mode Control (SMC) approach is seemed to have more remarkable achievement implemented in various applications [9-10]. Besides, SMC is recognized to has no appropriate method in obtaining its parameter and try and error method frequently utilized [11-13]. Hence, computational tuning methods such as Particle Swarm Optimization (PSO), Gravitational Search Algorithm (GSA), and Genetic Algorithm (GA) have been gradually noticed in the control field due to their notable performance in searching for the controller's optimal parameter [14-16].

It is observed in the study, the EHA system is generally applied to dealing with positioning control applications. The common applications including vehicle [17], robotic [18], construction machinery [19], and aerodynamic [20] required precise positioning control

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from the actuator. Thus, this paper aims to compare the positioning or trajectory tracking capabilities of the proposed controllers implemented in the EHA system. Furthermore, detailed analyses in terms of the controller effort and the error obtained from each controller are carried out.

This paper is organized as, modelling and control methods are briefly discussed in Section 2. The performance of each controller is presented in Section 3. Lastly, the summary of the outcome is drawn in Section 4.

## 2. PHYSICAL MODELLING

Until to date, two common types of transmission systems in hydraulic apparatus including pump operated and valve operated transmission systems are broadly used in the industry fields. In this study, the valve operated transmission system will be covered, since it is found to be performed efficiently nowadays [21]. This study is conducted based on the general structure of the EHA system as illustrated in Figure-1. Basically, the EHA system consists of actuator and sensing unit, valve or control unit, and computer control unit.

In the servo-valve, the spool in the servo-valve is driven by the motor. The torque of the motor is generated from the voltage, $V_v$ that drive the current, $I_v$ flow to the coil that connected to the servo-valve as expressed in (1).

$$V_v = \frac{dl_v}{dt} L_c + R_c I_v \tag{1}$$

where the coil consists of inductance and resistance as denoted in $L_c$ and $R_c$ respectively.

Electrical current that produces torque to the motor will generate the dynamic motion in the servo-valve that represented in a second-order form of differential equation as indicated in (2).

$$\frac{d^2 x_v}{dt^2} + 2\xi_v \omega_v \frac{dx_v}{dt} + \omega_v^2 x_v = I_v \omega_v^{\ 2} \tag{2}$$

Flow rate, Q controlled by the spool-valve in the chamber is generated through the orifice equation, which consists of different pressure, Pv, the position of the spool valve, $x_v$, and the gain of the servo-valve, $K_v$ as written in (3).

$$Q = K_v x_v \sqrt{\Delta P_v} \tag{3}$$

By neglecting the effect of internal leakage occur in the servo-valve, the fluid flow characteristic in each chamber represented in (4) and (5) [22].

$$Q_1 = \begin{cases} K_{v1} x_v \sqrt{P_s - P_1} & ; x_v \geq 0, \\ K_{v1} x_v \sqrt{P_1 - P_r} & ; x_v < 0, \end{cases} \tag{4}$$

$$Q_2 = \begin{cases} -K_{v2} x_v \sqrt{P_2 - P_r} & ; x_v \geq 0, \\ -K_{v2} x_v \sqrt{P_s - P_2} & ; x_v < 0, \end{cases} \tag{5}$$

where the servo-valve gain coefficient is assumed for a symmetrical valve as, $K_v = K_{v1} = K_{v2}$.

The pressure, $P_s$ supplied from the pump will drive to the servo-valve. In the evolution of the EHA system, it is commonly equipped along with pressure regulator nowadays, which can adjust the maximum operating pressure supported by particular applications. The pressure generated will form the dynamics between the pump and the servo-valve can be expressed as:

$$P_s = \frac{\beta_e}{V_t} (Q_{pump} - Q_L) dt \tag{6}$$

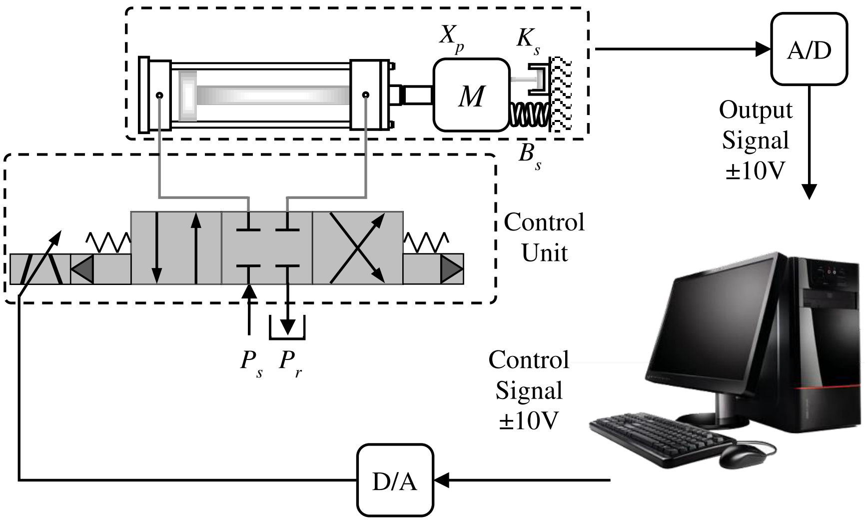


**Figure-1.** The common structure in the EHA system.

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where $\beta_e$ is the bulk modulus of the fluid, $V_t$ is the piping volume, which is connected between the pump and the servo-valve, $Q_{pump}$ is the constant flow rate from the pump volume, $Q_L$ is the flow rate of the servo-valve volume.
After the modelling of the EHA system, controller is designed to overcome the issue existed in the EHA system. The controllers that have been designed including PID, FOPID, and SMC controllers. Followed by the positioning or the trajectory tracking of each controller implemented in the EHA system which is the main objective of this study.

The discussions of the PID, the FOPID, and also the SMC controller have been carried out in the past study in [23], which is the study mainly focus on the robustness performance achieved by these controllers.

## 3. PERFORMANCES ANALYSES

The simulation works are performed using MATLAB/Simulink 2018 software. In the study, step response has been injected to examine the performance of the proposed controller. As mentioned earlier, this study is to examine the effort required to generate the output response as depicted in Figure-2.

Bear in mind that the controller's parameters are obtained using PSO algorithm, which are tuned only once imitating the real-time environment that required fast result. Thus, a well-designed controller is not only compensating the existing drawback of the system, but also capable of diminishing the actual effort needed to actuate the application.

Figure-2 depicts the output of the designed controllers including PID, FOPID, and SMC controllers. Based on the output response, the SMC controller is capable of outperforming the PID and the FOPID controllers. As clearly seen in the response, although the FOPID is well-known as an improved version of the PID controller, the output response generated by the FOPID controller is poorer than the PID controller. This might be due to the defect of the tuning algorithm that required the shortest time to searching for multiple or more gains. Thus, further analysis is essential which will be done in future.

In terms of the controller effort, the data are obtained between the controller and the system. Specifically, the output of the controller and the input of the system. Figure-3 depicts the controller effort of each controller.

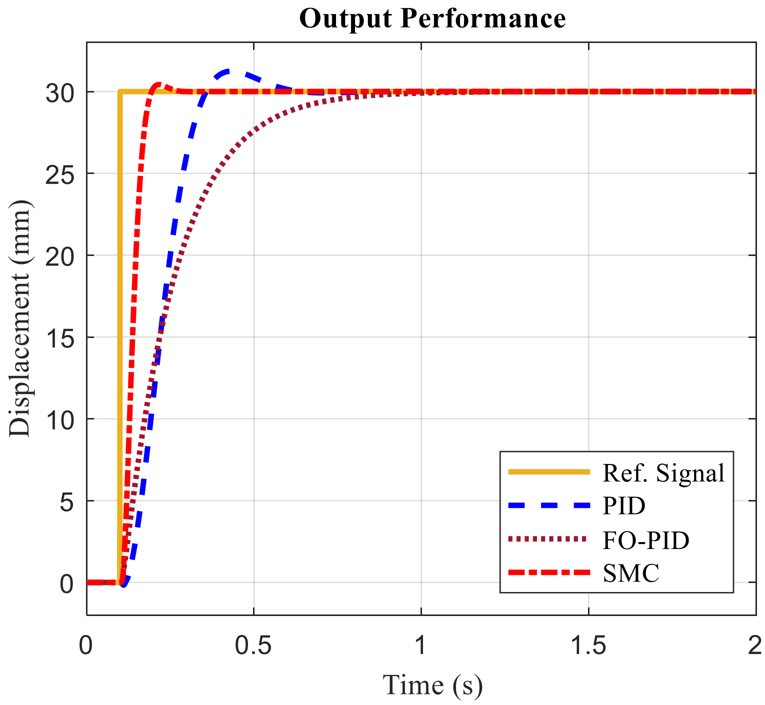


**Figure-2.** Trajectory tracking for the designed PID, FO-PID and SMC controllers.

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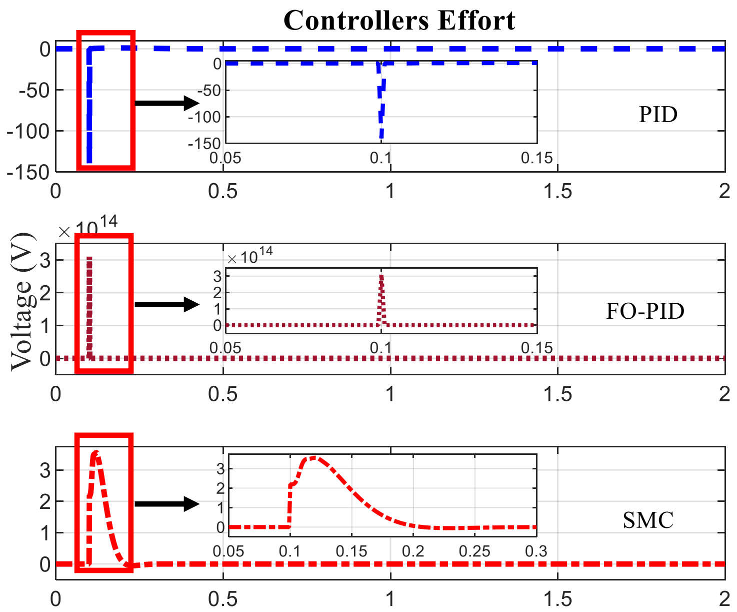


**Figure-3.** Controller effort for the designed PID, FO-PID and SMC controllers.

As can be seen in Figure-3, the numerical data shows the FOPID controller obtained the worst control effort, followed by PID and SMC. To further analyse the output response, the data were extracted by using the popular performance indices including Root Mean Square Error (RMSE), Integral Square Error (ISE), Integral Time Square Error (ITSE), Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE). The performance indices including ISE, ITSE, IAE, and ITAE have the equations below.

$$ISE = \int_0^\infty e^2(t)dt \tag{7}$$

$$ITSE = \int_0^\infty e^2(t)tdt \tag{8}$$

$$IAE = \int_0^\infty |e(t)|dt \tag{9}$$

$$ITAE = \int_0^\infty |e(t)|tdt \tag{10}$$

Noted that all the controller's parameters are obtained using PSO algorithm, which was tuned only once as listed in Table-1.

The numerical data with respect to Root Mean Square Error (RMSE), or with respect to the voltage, or generally speaking, the effort required to drive the EHA system are tabulated in Table-2. The data clearly show the FOPID obtained worst performance which is approaching unstable condition.

**Table-1.** Parameters obtained using PSO algorithm

| Controller | Parameter | | | | |
|---|---|---|---|---|---|
| | $K_p$ | $K_i$ | $K_d$ | $\lambda$ | $\delta$ |
| **PID** | 10.0910 | 0.0013 | -4.6985 | 1 | 1 |
| **FO-PID** | 34.8991 | 0.7052 | 8.5401 | 2.0296 | 8.1205 |
| **SMC** | - | - | - | 87.6240 | 395.7009 |

**Table-2.** Root mean square error with respect to voltage

| Controllers | Root Mean Square Error (Voltage) |
|---|---|
| **PID** | 3.1558 |
| **FOPID** | $6.9289 \times 10^{12}$ |
| **SMC** | 0.4893 |

In terms of the performance indices with respect to the error, all the data show the SMC is capable of generating the smallest error as listed in Table-3.

In terms of the performance indices with respect to voltage, the SMC also outperform the PID and the FO-PID controllers as tabulated in Table 4. However, in a real-time application, it might be only either one of the criteria. Generally speaking, highest precision required highest effort. Thus, this subject required further study, which is implemented in a real-time application.

**Table-3.** Performance index with respect to error

| Analysis / Controller | IAE | ITAE | ISE | ITSE |
|---|---|---|---|---|
| **PID** | 0.00394 | 0.00075 | $8.23513 \times 10^{-05}$ | $1.29177 \times 10^{-05}$ |
| **FOPID** | 0.00494 | 0.00126 | $7.87748 \times 10^{-05}$ | $1.40427 \times 10^{-05}$ |
| **SMC** | 0.00122 | 0.00015 | $2.58884 \times 10^{-05}$ | $3.04924 \times 10^{-06}$ |

**Table-4.** Performance index in terms of voltage

| Analysis / Controller | IAV | ITAV | ISV | ITSV |
|---|---|---|---|---|
| **PID** | 0.22310 | 0.04781 | 4.53932 | 0.46953 |
| **FOPID** | $6.88390 \times 10^{10}$ | $6.88390 \times 10^{10}$ | $2.13366 \times 10^{25}$ | $2.13366 \times 10^{24}$ |
| **SMC** | 0.18473 | 0.02460 | 0.48685 | 0.06117 |

## 4. CONCLUSIONS

The positioning or trajectory tracking and the controller effort of the designed PID, FO-PID, and SMC controllers are evaluated in this study. The mathematical modelling of the EHA system is also presented in the study. Then, the controller is designed under the nonlinear and the uncertain characteristics of the EHA system. The precision in the positioning tracking is well-known to be crucial, which is interrelated with the controller effort. Sometimes, it can be either achieved one of the criteria, which is considered as a trade-off between the precision and the controller effort. Based on the results, SMC is capable of achieving smallest error with smallest effort, which indicates it’s tracking capabilities in delivering better outcomes compared to the PID and the FO-PID controllers.

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