Tracking Performance of Pneumatic Position Using Fractional-Order $PI^\lambda D^\mu$ Controller

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Abstract. An Intelligent Pneumatic Actuator (IPA) system is known to be highly nonlinear, subject to nonlinearities which make it difficult to control the precise position of the actuator. Thus, system modelling is crucial in creating a mathematical model that demonstrates the dynamics of a system. In this study, the pneumatic system has been modelled by an autoregressive with exogenous input (ARX) model structure, while PID and fractional orders $PI^\lambda D^\mu$ (FOPID) were used as control strategies. Finally, a simulation-based comparative analysis was evaluated and addressed to decide which controller provides a better tracking performance (Steady State Error ($e_{ss}$), Percentage of Overshoot ($%Os$), Settling Time ($Ts$), and Rise Time ($Tr$)).

1. Introduction
The intelligent pneumatic actuator chosen for this analysis has a variety of benefits, including the ability to interact and control local functions while minimizing the number of cables attached, and having more intricate, high-performance actuator motions [1], [2]. This actuator has a different trait from most of the pneumatic actuators that have full extend and contract capabilities. The pneumatic stroke in this actuator can be controlled accordingly. Unfortunately, pneumatic actuators must deal with high friction forces, dead time (due to air's compressibility), valve dead zone concerns, mass flow rate specifications, conformity variance, and producing force [3], [4]. These nonlinearities and uncertainties make modelling and precise position control of a pneumatic actuator difficult to attain [5]. Many researchers have explored the use of various control protocols in pneumatic systems thoroughly in order to address these difficulties. The pneumatic mechanism must be modelled in order to construct the controller. These models are implemented in the design control explicitly or indirectly. Overall, there are two approaches to evaluate machine mathematical modelling. The first approach is a systematic study of the law of nature. The second approach is to use the system identification techniques developed by the innovation model's experiments. Linear controllers such as PID controllers, pole-placement controllers, intelligent controllers (fuzzy and neural networks), predictive controllers, and so on were studied in the early stages of controller design [6]–[10].
In recent years, interest in Fractional Order PID (FOPID) control, the enhanced version of PID control, has grown gradually. FOPID control has a straightforward control architecture that is similar to conventional PID control but more modular, which is particularly useful for systems with nonlinear dynamics and unknown parameters [11]. In addition, the presence of two additional tune-enabled derivative and integral orders has improved the versatility of FOPID relative to PID control, in particular by minimizing residual steady-state oscillation and retaining system stability [12]. The results of these observations are that FOPID controller has been applied in a variety of programmers, including robotic systems, power generation, thermal system and permanent magnet brushless motor. However, the FOPID controller factors chosen is a potential concern because all five factors requires proper matches to attain the desired performance and consistency [13].

The main objective of this research is to create a model and design the pneumatic system controller. The pneumatic system model in the transfer function is acquired through the System Identification (SI) method. The design of the FOPID was chosen as the pneumatic system's new control technique. Controller performance evaluation was conducted with MATLAB simulation.

The paper has been organized: Section 2 experimental setup. Section 3 represents the dynamic model of the IPA. Section 4 discusses the controller design (FOPID). The simulation results to verify the system performance with the suggested control technique are introduced in section 5. Eventually, section 6 presents with some final remarks.

2. Methodology

2.1. Experimental Setup

A laser stripe code, optical sensor, pressure sensor, valves, and Programmable System on Chip (PSoC) control board are the components of the pneumatic actuator that is used in this research. The pressure sensor and on/off valves mounted to the cylinder's end are used to monitor the pressure in the chamber and monitor the cylinder's air flow, respectively. A KOGANEI-ZMAIR optical sensor identifies the location of the cylinder rod, and a laser stripe code with a smaller pitch of 0.01mm was calculates its value. The second chamber's valve is operated by a Pulse-Width Modulator (PWM) signal, and the service cycle of this PWM signal is critical for the cylinder's right and left motions.

Figure 1 illustrates the experimental setup for this analysis. Using the National Instrument (NI) Data Acquisition (DAQ) card PCI/PXI-6221 (68-Pin) desk, SHC68-68-EPM cable and SCB-68 M series modules, the pneumatic actuator system and the Personal Computer (PC) (MATLAB platform software) interact.

![Figure 1. The experimental setup of the system.](image)
2.2 System Modelling
A study consisting of the pneumatic actuator method described previously was performed in real time and 1600 input and output data measurements were obtained using system identification method. The first 800 samples for training while 800 samples for validation. The sampling time (Ts) utilized during collection of the input and output data is 0.01s. Figure 2 displays the plot of both loaded and obtained data.

![Input and output signals](image)

**Figure 2.** Input and output data of the system.

Several parametric model constructs, such as auto-regressive with exogenous input (ARX), auto-regressive moving average with exogenous input (ARMAX), box Jenkins (BJ), and output error (OE), can be used to describe the system in system identification [14]–[16]. Only ARX is used as a reference framework to reflect the structural calculation of the IPA system in this analysis. Based on its Best Fit and Akaike’s Final Prediction Error (FPE), the mathematical model obtained is validated. This would be achieved by evaluating the data obtained during the simulation. The discrete ARX transfer function that used in this analysis is described in Equation (1).

\[
\frac{B_{\text{Position}}(Z^{-1})}{A_{\text{Position}}(Z^{-1})} = \frac{0.1187 Z^{-1} - 0.235 Z^{-2} + 0.1169 Z^{-3}}{1 - 2.99 Z^{-1} + 2.981 Z^{-2} - 0.9917 Z^{-3}}
\]

(1)

Figure 3 depicts the layout of the calculated (identified) model performance. Figure 4 depicts the zero-pole point of the established third-order ARX model.
The model plant is valid as the compatibility is more than 90%. From Figure 3, the best fit of the output model is 90.75% whereas the Akaike’s FPE of the ARX331 model is lesser at 0.04293. that means the model of IPA that we got is acceptable.

2.3 FOPID Controller

The FOPID control, as described earlier, is an expansion of the classic PID control. In the derivative and integral terms, two additional non-integer orders (λ and μ) are introduced in this control method. By using fractional calculus, the FOPID control is an efficient way to improve the durability and stability of conventional PID control [13], [17]. Equation (2) can be used to describe the FOPID control scheme.

\[
C(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{S^\lambda} + K_d S^\mu
\]  

(2)
where $C(s)$ is control signal of FOPID controller, $E(s)$ is errors between the relation and the real pitch position in the Laplace variable, while the $K_p$, $KI$, $\lambda$, $KD$, and $\mu$ are representative of the tunable parameters of the FOPID control.

The two additional tuning parameters ($\lambda$, $\mu$) provide additional flexibility for tuning the controller, which improves the precision and robustness of the control operation. Figure 5 illustrates the variety of these values in detail. Based on the value of integral and differentiator can know the type of controller. The controller is proportional controller when the value of ($\lambda$, $\mu$) is (0,0), PD controller when the values are (0,1), PI controller when the values are (1,0), while PID controller when the values are (1,1).

![Figure 5. PID controllers with fractional-orders](image)

Figure 6 displays the IPA model with the controllers in MATLAB SIMULINK. The main goal of controller is to hold the IPA position in its optimal position.

![Figure 6. IPA with PID and FOPID controllers.](image)

3 Results and Analysis

The model developed for IPA is controlled with both the classic PID and FOPID controller. The transfer function of IPA that got from system identification is described in equation (1). Table 1 includes the values of the PID and FOPID parameters that were tuned and used in this research.
Table 1. The values of PID and FOPID parameters.

| Criterion | $K_P$ | $K_I$ | $K_D$ | $\lambda$ | $\mu$ |
|-----------|-------|-------|-------|-----------|-------|
| PID       | 15    | 1     | 5     | -         | -     |
| FOPID     | 15    | 1     | 5     | 0.4       | 0.6   |

Table 2 displays the system performance ($T_s$, $T_r$, $OS\%$, and $T_p$) in the time domain after applied PID and FOPID controllers.

Table 2. Simulation result of PID and FOPID

| Criteria               | Controllers |
|------------------------|--------------|
|                        | PID          | FOPID       |
| Rise Time, $T_r$ (s)   | 0.8717       | 0.7992      |
| Settling Time, $T_s$ (s)| 1.7638       | 0.9791      |
| Overshoot, $OS\%$      | 0.9150       | 0.0962      |
| Peak Time, $T_p$ (s)   | 3            | 1           |

Figure 7. PID and PI$^D$ Tuned Response
The idea was to first determine the optimal parameters for the conventional PID control algorithm and then to use these optimal parameters as known parameters for FOPID control algorithm in order to determine optimal exponents of differentiation and integration ($\lambda$, $\mu$).

Several strategies based on different control theories were recently proposed for the problem of IPA position control. Some of strategies showed an increased steady-state error and some of them recorded a longer settling time to achieve steady-state value.

In this study, The findings in Table 2 and Figure 7 reveals the FOPID is more effective and produces a more efficient response than a conventional PID controller. The implementation of fractional orders has established an accelerated response rise and settling time, enhancing the controller performance. The result shows that FOPID has 0.0962 of %OS and approximately 0 value of $e_{ss}$ while PID has 0.9150 of %OS and also has approximately 0 value of $e_{ss}$. The value of $T_r$ is 0.7992 s for FOPID and 0.8717 s for PID. The value of $T_s$ shows that FOPID gives 0.7847 s faster respond compared to PID where the value of $T_s$ is 0.9791 s. By comparing both integer-order and fractional-order control time-domain performances, FOPID is found to effectively surpass the conventional method, by settling quickly to the required reference.

4 Conclusion

In this paper, the system identification toolbox is utilized in developing the intelligent pneumatic actuator model. In addition, the controller designed by using $PI^\lambda D^\mu$ Controller is used and presented. The performance of PID and FOPID are compared on their settling time ($T_s$), rise time ($T_r$), peak time ($T_p$), percentage of overshoot ($OS\%$), and percent steady state error ($e_{ss}$). The simulation result found that $PI^\lambda D^\mu$ controller gives better control performance in terms of zero percentage of overshoot and percent steady state error compared of PID controller.

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