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Construction and Evaluation of a Control Mechanism for Fuzzy Fractional-Order PID

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Abstract: In this research, a control mechanism for fuzzy fractional-order proportional integral derivatives was suggested (FFOPID). The fractional calculus application has been used in different fields of engineering and science and showed to be improved in the past few years. However, there are few studies on the implementation of the fuzzy fractional-order controller for control in real time. Therefore, for an experimental pressure control model, a fractional order PID controller with intelligent fuzzy tuning was constructed and its results were calculated through simulation. To highlight proposed control scheme advantages, the performances of the controller were inspected under load disturbances and variations in set-point conditions. Furthermore, with classical PID control schemes and fractional order proportional integral derivative (FOPID), a comparative study was made. It is revealed from the results that the suggested control scheme outclasses other categories of the control schemes.

Keywords: fractional-order control; pressure control; PID controller; pressure system identification; fuzzy logic control

1. Introduction

Ever since the middle of the last century, proportional-integral derivative (PID) controllers have been used in the control of a number of industrial processes. Zeigler and Nichols [1], during the 1940s, launched the popular method for tuning PID controllers based on the transient response characteristics of a given plant. Many engineers and scientists followed them and developed adjustment methods applied to the synthesis of PID controllers [2–5]. So far, the engineering community has mostly dedicated time on expressing systems using optimizing the formulation of integer order differential equation and analysis technique utilizing a variation of numerical and analytical solutions. Recent advances in the hardware application of elements of a fractional order [6–8] have sparked a fresh interest in the analysis and demonstrating of a new fractional order system class that examines natural phenomena from a completely different perspective. For the past 300 years, there has been a theory for fractional order systems [6].

Therefore, the advancements in analysis and demonstrations of the fractional-order systems and related hardware application in the last few years have greatly increased the studies on the fractional-order (FO) control system [9–11]. In the past decades, much research has observed fractional-order plants in various branches of engineering and sciences. Electromagnetic waves, dielectric polarization, heat diffusion systems, fluid mechanics, transmission lines, electrode–electrolyte polarization, viscoelastic systems, spectral densities of music, cardiac rhythm, viscoelastic systems, and various other plants have been discovered to exhibit fractional-order dynamics in interdisciplinary research areas [12–15]. FO systems were constructed by adding fractional powers to integer order differential equations in derivative and integral terms, and they are one of the modified variants of integer-order (IO) [6]. For instance, the derivative (KD), integral (KI), and
proportional (KP) constants are present in the fractional-order PID controller, along with two additional constants, a differentiator of order $\mu$ and an integrator of order $\lambda$ [16,17]. According to recent research, the FO control scheme provides an improved substitute to traditional integer-order control for control applications in industrial in terms of precision and robustness [18–22].

Liu et al. [23] presented a fractional fuzzy PID control algorithm for common industrial temperature control systems to improve the production quality and accuracy of control models. A basic system of fractional orders is used to describe the temperature control process. The temperature profile controlled by the proposed algorithm can achieve more satisfactory dynamic performance and better robustness to environmental changes caused by internal and external disturbances.

Most of the industrial processes are complex and have strong nonlinearity. Hence, it is challenging to develop an accurate mathematical model to design a classical controller and obtain satisfactory control performance. In order to overcome these issues, a self-tuning and adaptive mechanism is necessary for classical controllers. The fuzzy set theory gives maximum flexibility in developing intricate applied control methods. In fuzzy set-theory, to express the observations, easier linguistic notations are used. The Fuzzy Logic turned the design of controller to be simple and yet for more complicated and nonlinear industrial process without using the particular mathematical representation of the system [24]. Additionally, the plant parameters are varying [25,26]. The classical controller is combined with FLC for guarantee optimum performance and fine-tuning parametric gains owing to non-linearities and load turbulences.

Jegatheesh and Kumar [27] proposed a study to control the liquid level of Two Tank Spherical Interacting System where they posited Fuzzy Fractional Order Proportional Integral Derivative (FFOPID) controller. Experimental outcomes prove that FFOPID is superior to all other existing methods in terms of various time domain specifications and time integral performance measurements.

In power plants, chemical industries, well drilling, and automobiles pressure control is vital. In industries, the pressure plants usually intersect and operates at various pressure levels. Moreover, these pressure plants are often exposed to the rapid variations in the load. Hence, there is a requirement for an effective control scheme to avoid the difficulty of free operation. In earlier days, industries used to regulate the pressure through traditional control techniques, for example, proportional integral (PI) or proportional integral derivative (PID), Ardjal et al. [28] proposed a combination of control methods, which are model free controller, Fractional-order proportional integral controller, and fractional order sliding mode controller, which uplift the MFC algorithm with the term MF-FOiPI-FOSMC called Model Free-Fractional Order Intelligent Proportional Integral-Fractional Order Sliding Mode Controller. However, results of the traditional control plans are only appropriate for simple systems with a definite operating interval and not appropriate for disturbance in load and constant variations in set points [29–31].

As a result, the FOPID controller was created, which is a modified PID control structure. The orders of integrals and differentiation in a traditional IOPID controller are constrained to integers, which might limit the controller’s performance, especially when the system includes plant uncertainty and load disturbances [32]. The integrator and differentiator orders of the FOPI D controller are real non-integer numbers. Fractional-order controllers have been employed by many researchers since their introduction, who have proved their superior performance over integer-order controllers [16]. Vinu et al. [33] proposed fractional-order PID control approach optimized by Harmony search, which was recently proved to be superior to traditional controllers in monitoring the speed of a DC engine in energy component-controlled vehicles under powerful burden circumstances.

As a consequence, a one-of-a-kind model for exploratory arrangement was made, and the framework’s exhibition is shown involving a FFOPID regulator for load unsettling influences and varieties in set-point level, adding to pneumatic strain control research. The FFOPID control system’s performance is also compared to that of FOPID and classic
PID control systems. The use of fractions has increased in the engineering and scientific fields and has proven to be superior. A study by Al Dhaifallah [34] considers a fuzzy PID controller of fractional order. In addition, the behavior of the controller is investigated using the tubular heat exchanger process. The comparison is made using the traditional PID control structure. Simulations show that the presented control method is superior to traditional PID control structures. The pneumatic pressure is one of the vital variables used in industries similar to chemical reaction control, pneumatic positions, well drilling, servo systems, power plants, heating, ventilating and air conditioning systems, automobile, and so on. Due to the compressibility of air, load fluctuations, and outside disturbances, pneumatic pressure plants have extremely nonlinear dynamic properties. Additionally, industrial pneumatic pressure plants often operate at various pressure levels and are linked. As a result of the uncertainties and nonlinearity present, the exact control of pressure plants is difficult [35–37]. Taking the above aspects into consideration, a fuzzy-based FOPID control scheme is proposed by the current study to respond faster and have better control performances. To show the performance of the proposed control technique, the current study develops a novel pneumatic pressure system model, and a system performance is studied under load disturbances and changes in set-point conditions.

2. Materials and Methods

Pneumatic System

Pneumatic pressure is a critical variable in a variety of industries, including power plants, chemical reaction control, pneumatic position servo systems, well drilling, heating, ventilation, air conditioning systems, and automobiles. Due to the compressibility of air, load fluctuations, and external disturbances, the dynamic characteristics of pneumatic pressure plants are highly nonlinear. In addition, industrial pneumatic pressure plants are frequently interconnected and operate at various pressure levels. As a result of the uncertainties and non-linearity, precise control of a pressure plant is difficult. As a result, for trouble-free operation of the pneumatic system in industries, an effective control strategy is required. Because of their advantages, traditional PI and PID controllers have been widely employed in industrial applications in the past.

Current FO control research trends point to the use of a fuzzy with FO control strategies to increase control performance. When it comes to building sophisticated industrial control systems, the rule-based fuzzy set theory gives you additional options. Linguistic notations are used in fuzzy set theory to concisely convey observations and construct a control framework. Without knowing the complete mathematical description of the system, the construction of a fuzzy logic controller (FLC) is becoming easier, even for more complex and nonlinear industrial processes. FLC is also used in conjunction with the FO controller to fine-tune parametric gains and ensure optimal performance in the face of nonlinearities, load disturbances, and changes in plant parameters. A fuzzy-based FOPID control method is developed for faster reaction and better control performance, taking into account all of these factors. A pneumatic pressure system model is built and the system performances are evaluated under load disturbances and changes in set-point circumstances to demonstrate the performance of the proposed control technique.

3. Overview of System

Figure 1 portrayed the experimental setup schematic diagram. It contains pressure controller, electro-pneumatic control valve, pressure marker, controller connecting units, air blower, and strain transmitter.

The constant pressure is maintained by the pressure regulator, which is connected with the air compressor. The air compressor is also then connected to 50 mm electro-pneumatic control valve, which manages the incoming air flow to the pressure storage. Precision pressure transmitter is used to measure the pressure in the tank. A current signal ranging from 4 to 20 mA is outputs by the pressure transmitter, based on the tank pressure. The pressure tank is intended to operate at a maximum pressure of 5 bar. The same proportion
electro-pneumatic control valve linked at the intake side regulates pressure tank air flow. For the control valve, which is run via a 4 to 20 mA current signal, changing its positions may create the required pressure inside the tank. A pressure indicator is also mounted on the top to manually read the tank pressure. Voltage to current (V to I) converters, current to voltage (I to V) converters, and current to pressure (I to P) converters are among the interface units. Figure 2 shows a preview of trial arrangement for the strain control.

![Figure 1. Pneumatic pressure control, schematic diagram.](image1)

![Figure 2. Picture of pneumatic pressure control experimental setup.](image2)

4. Pneumatic Pressure Control System Modelling

4.1. Model for Integer Order

The open loop trial information is used to decide the model of the exploratory framework. Experimentation may be used to determine the process model and understand the changing nature of a process in order to create control systems. The process is assumed a single-input single output (SISO) system for framework identification. The Cohen–Coon (CC) approach was used to find the ordinary order process model [37]. To acquire the interaction realization for a first-order process alongside transport lag, the most suitable option is the CC methodology. In the process identification, the strain control framework is approximated as a first-request process with transport delay and is given by:

\[
G_P (s) = \frac{K_p e^{-T_d s}}{1 + Ts}
\]  

(1)

In Equation (1), Td is the delay in the transport, \( K_p \) is gain in process, and T is constant time process. The IO model parameters of expression (1) are estimated using CC method and the system is observed as having a transport delay (Td) of 1.4 s.
4.2. Fractional Order Model

In the past years, there have been several greater amounts of accomplishments in the field of FO system identification. FO differential equations are commonly used to represent FO systems in the time domain.

\[ a_n D^{\alpha_n} y(t) + a_{n-1} D^{\alpha_{n-1}} y(t) + a_{n-2} D^{\alpha_{n-2}} y(t) + \ldots + a_0 y(t) = u(t) \] (2)

The system input is \( u(t) \), whereas the system output is \( y(t) \). \( \alpha_n, \alpha_{n-1}, \ldots \alpha_1 \) are fractional in Equation (2), the orders of differentiation. That is, \( \alpha_n, \alpha_{n-1}, \ldots \alpha_1 \) could be real valued and not only integers. The Grunwald–Letnikov definition may be used to get the numerical solution for (2). The derivatives of the fractional model (1) are calculated using Grunwald–Letnikov approximation techniques [36]. The system that has been found is listed below (3).

\[ G_p(s) = \frac{7.01}{11.39s^{0.72}} + 1 \] (3)

5. Controller Design

5.1. Integer Order PID Controller

To achieve good control, the controller parameters must be chosen carefully and at their optimum value. During load disturbances and changes in set-point, a good controller should have the least amount of overshoot and settling time possible. To find the controller settings for the pressure control system, the Cohen–Coon controller tuning approach was used. The Cohen–Coon tuning rules are more versatile than the Ziegler–Nichols tuning rules and can be applied to a wider range of processes. Only processes with a dead time of less than half the length of the time constant perform well with the Ziegler–Nichols rules. The following expressions could be used to find the controller parameters:

\[ K_c = \frac{1}{K_p} \frac{T}{T_d} \left( \frac{4}{3} + \frac{T_d}{4T} \right) \] (4)

\[ \tau_I = T_d \frac{32 + 6T_d/T}{13 + 8T_d/T} \] (5)

\[ \tau_D = T_d \frac{4}{11 + 2T_d/T} \] (6)

The above equation computed value of (\( \tau_I \)) integral time is 3.3, (\( K_c \)) namely gain is 1.2 and (\( \tau_D \)) derivate time is 0.49.

5.2. Fractional-Order PID Controller

The differentiator of fractional-order can be characterized as a continuous differ-integral operator, which is expressed as:

\[ _aD^r_t = \begin{cases} \frac{d^r}{dt^r}: r > 0 \\ 1: r = 0 \\ \int_a^t (d\tau)^{-r}: r < 0 \end{cases} \] (7)

The well-known derivatives of Liouville, Riemann–Liouville, and Caputo naturally extend into complex function spaces, establishing interesting connections between them and the derivatives of Grünwald–Letnikov. The boundaries of the non-integer order basic operator
are a and t. The Grunwald–Letnikov (GL), the Riemann–Liouville (RL), and the Caputo definitions are all fractional differ-integral techniques. The following is the GL definition:

\[ aD^t_t f(t) = \lim_{h \to 0} \frac{[t-a]}{h} \sum_{j=0}^{\lfloor t/a \rfloor} (-1)^j \binom{r}{j} f(t - jh) \]  

(8)

The definition of RL is as follows:

\[ aD^t_t f(t) = \frac{1}{\Gamma(n-1)} \frac{d^n}{dt^n} \int_a^t \frac{f(\tau)}{(t-\tau)^{r-n+1}} d\tau \]  

(9)

The Caputo definition is as follows:

\[ aD^t_t f(t) = \frac{1}{\Gamma(r-n)} \int_a^t \frac{f^{(n)}(\tau)}{(t-\tau)^{r-n+1}} d\tau \]  

(10)

\((n-1 < r < n)\) and \(\Gamma(m)\), the well-known Gamma function is explained for positive real m by the following equation.

\[ \Gamma(m) = \int_0^\infty e^{-u}u^{m-1}du \]  

(11)

In Caputo derivatives, the beginning conditions for integer-order and fractional-order differential equations are the same. Take an appropriate \(n\) order integer derivative of \(m\) order non-integer integral to get a \(n - m = q\) order one to get the definition of fractional derivative:

\[ \frac{d^q f(t)}{dt^q} = \frac{d^{n-m} f(t)}{dt^{n-m}} = \frac{1}{\Gamma(m)} \int_0^t (t-y)^{m-1}f(y)dy \]  

(12)

The equation above becomes a canonical first-order derivative. If \(q = 1\) \((n = 2, m = 1)\). Therefore, the FOPID regulator is comprised of partial administrators with regulator gains. The FOPID regulator move capacity might be communicated as utilizing fragmentary vital and partial subordinate terms.

\[ G_c(s) = \frac{u(s)}{e(s)} = K_P + K_I s^{-\lambda} + K_D s^\mu \]  

(13)

where \((\lambda, \mu)\) is greater than zero. This regulator offers higher tuning adaptability, permitting it to cover a more extensive scope of boundaries to settle the plant taken care of and further develop control circle power. The same research has been conducted to corroborate this feature (see, for example, [38–40]), and in the following sections, the research will look at several innovative pieces of literature addressing fractal resilience. \(G_c(s)\) is the transfer function of controller, \(e(s)\) is the error, and \(u(s)\) is the yield in Equation (13). The constants for proportional, integral, and derivative expressions are KP, KI, and KD. The fractional component of integral parts is \(\lambda\), while the fractional component of derivative parts is \(\mu\). In time-domain, representation (13) is written as:

\[ u(t) = K_P e(t) + K_I D^{-\lambda} e(t) + K_D D^\mu e(t) \]  

(14)

Apart from the typical three parameters KP, KI, and KD, it is self-evident that two additional parameters derivative order and integral order should be addressed in the design of FOPID controller. To get optimum controller settings, we use the Nelder-mead ap-
proach [41] with the performance metric of Integral of Absolute Error (IAE). The estimated FOPID controller values are shown in Table 1.

Table 1. Parameters for FOPID controller.

<table>
<thead>
<tr>
<th>KP</th>
<th>KI</th>
<th>λ</th>
<th>KD</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.34</td>
<td>0.19</td>
<td>0.91</td>
<td>0.28</td>
<td>0.87</td>
</tr>
</tbody>
</table>

5.3. Fuzzy Fractional-Order PID (FFOPID) Controller

The Fuzzy Fractional-Order PID (FFOPID) regulator is a blend of rule-based fluffy framework with fragmentary request PID (FOPID) control. Figure 3 demonstrates the structure of the FFOPID control scheme. In this control structure, the rule-base fuzzy system takes the error and change-in-error input parameters at individual sampling and generates three output signals corresponding to KP, KI, and KD of FOPID controller. In fact, the fuzzy system fine-tunes gain values of KP, KI, and KD online based on the system dynamic. This online tuning technique makes the system stabilize quickly at the desired level.

During load variations and changes in set-point circumstances, the online gain amendment type control scheme will guarantee that the system’s static and dynamic characteristics are maintained. In the FFOPID controller, the ultimate amount of controller gains may be stated as

\[
\begin{align*}
\Delta K_P &= K_P + \lambda e(t) \\
\Delta K_I &= K_I + \Delta K_P \\
\Delta K_D &= K_D + \Delta K_D
\end{align*}
\]

For inputs and outputs, a triangle shape membership function is used. Three membership functions are chosen for inputs, and five membership functions are picked for each output to generate an accurate output. Figure 4 demonstrates the membership functions which are the language variables NB (negative large), NS (negative small), N (negative), Z (zero), P (positive), PS (positive small), and PB (positive large). The formula to normalize values is in Figure 4a,b.

\[
x'' = 2 \times \left\{ \left( x' - \text{min}(x) \right) / \left( \text{max}(x) - \text{min}(x) \right) \right\} - 1
\]
Further, the Mamdani type fuzzy inference system is used while designing the proposed fuzzy system. Rajani and Nikhil [42] suggested the techniques for framing rule base via intuitive logic. The rule-base used in the proposed fuzzy system to produce suitable gain factor for the three outputs is shown in Table 2.

**Table 2. Fuzzy linguistic rule-base.**

<table>
<thead>
<tr>
<th>$\Delta Kp$</th>
<th>$\Delta e$</th>
<th>$\Delta Kd$</th>
<th>$\Delta ki$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta e$</td>
<td>NE</td>
<td>ZE</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>NE</td>
<td>NB</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>ZE</td>
<td>NB</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>NS</td>
<td>ZE</td>
</tr>
<tr>
<td>$\Delta Kd$</td>
<td>NE</td>
<td>ZE</td>
<td>P</td>
</tr>
<tr>
<td>$\Delta Ki$</td>
<td>NE</td>
<td>ZE</td>
<td>P</td>
</tr>
<tr>
<td>$\Delta Ki$</td>
<td>NE</td>
<td>NB</td>
<td>NS</td>
</tr>
<tr>
<td>$\Delta Ki$</td>
<td>ZE</td>
<td>ZE</td>
<td>PS</td>
</tr>
<tr>
<td>$\Delta Ki$</td>
<td>P</td>
<td>ZE</td>
<td>PS</td>
</tr>
</tbody>
</table>

The linguistic variables, namely NE (negative), NS (negative small), NB (negative big), ZE (zero), PB (positive big), P (positive), and PS (positive small), represent various fuzzy sets of input and output. The center of gravity de-fuzzification technique is selected to specify the crisp output.

**6. Simulation**

Simulation studies for the selected system model are conducted using MATLAB software to validate the performance of the suggested control strategy. Figure 5 shows the system response for unit step input using a normal PID controller, a FOPID controller, and a FFOPID controller. The FFOPID controller’s initial gain settings are determined by the FOPID controller parameters. Figure 5 demonstrates that the FFOPID controller outperformed the different type of controllers in terms of step response. Because of the online gain adjustment, it is clear that the fuzzy mixed fractional-order PID controller settles system output faster than different types of controllers.

![Figure 5. Step response of various controllers.](image-url)

To verify the functionality of the controllers used, numerous scenarios are used in the analysis, and controller comparisons and analysis of the initial results caused by this scenario were analyzed and investigated [43–45].

On the contrary, system response of a traditional PID controller creates overshoot, and a FOPID controller takes longer to reach steady state than an FFOPID controller. Based on the simulation findings, the fuzzy fractional order PID controller appears to be the best choice for regulating pressure in pneumatic systems.
Load disturbances are supplied in steady state to test the controller’s resilience for pressure control applications. Figure 6 depicts the outputs of different controllers for load disturbances, whereas Figure 7 depicts the corresponding control signal of various controllers for load disturbances.

**Figure 6.** Response of load disturbance using different controllers.

**Figure 7.** Load disturbance response of control signal of different controllers.

The FFOPID controller quickly follows the parameter variations and brings the system to a steady state condition, as seen by the load disturbance response. Figures 8 and 9 exhibit the controllers’ performance for set-point change, associated with control signals for various control schemes. It has been discovered that the suggested FFOPID control scheme adapts to new set point values better than other kinds. Table 3 shows a mathematical comparison of several controllers utilizing settling time, overshoot, and error criteria. The FFOPID control scheme is superior for the specified application, according to the results.

**Table 3.** Controllers’ performance summary.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Settling Time</th>
<th>Overshoot</th>
<th>ISE (Integral Square Error)</th>
<th>IAE (Integral Absolute Error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFOPID</td>
<td>3.5</td>
<td>0%</td>
<td>1.64</td>
<td>1.96</td>
</tr>
<tr>
<td>FOPID</td>
<td>5</td>
<td>0%</td>
<td>1.74</td>
<td>2.16</td>
</tr>
<tr>
<td>PID</td>
<td>7</td>
<td>8%</td>
<td>2.0</td>
<td>2.43</td>
</tr>
</tbody>
</table>
Figure 7. Load disturbance response of control signal of different controllers. The FFOPID controller quickly follows the parameter variations and brings the system to a steady state condition, as seen by the load disturbance response. Figures 8 and 9 exhibit the controllers’ performance for set-point change, associated with control signals for various control schemes. It has been discovered that the suggested FFOPID control scheme adapts to new set point values better than other kinds. Table 3 shows a mathematical comparison of several controllers utilizing settling time, overshoot, and error criteria. The FFOPID control scheme is superior for the specified application, according to the results.

Figure 8. Change in set-point different controllers’ response of change in set-point.

Figure 9. Control signal for change in set-point response of different controllers.

7. Conclusions

The retrieved results showed the superior performance of the FFOPID controller by improving the transient stability after the failure that caused the isolation. Simulation results confirm the effectiveness of the FFOPID controller in a system in multiple scenarios with superior stability and robustness compared to fuzzy logic PID controllers (FLPIDs) and PID controllers. For a unique pneumatic pressure control system model, a fuzzy logic based fractional-order PID controller was created and explored. Different control techniques have been used to manage pressure, and their effectiveness has been assessed through simulation. The FFOPID fuzzy logic system improves controller performance by using an online gain adjusting technique. The results show that changing controller parameters live using a rule-based fuzzy system improves the fraction order controller’s resilience and flexibility for pressure control applications. Furthermore, this control method is easy and efficient, and it may be utilized as a superior replacement to existing FOPID and traditional PID controllers for improved performance. The results demonstrate that the FFOPID control system is superior in regards to pressure control. The controller settings may be modified online based on the disturbance and uncertainty model generated by environmental changes.
To demonstrate the dominance of the proposed control strategy, samples of the noted temperature control system are also shown. The proposed method's digital algorithm will be implemented in the future utilizing a microprocessor or microcontroller, as this simulation study is only the first phase in the research.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The author is very thankful to all the associated personnel in any reference that contributed in for the purpose of this research.

**Conflicts of Interest:** The authors declare no conflict of interest.

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