Modelling and Controlling of position for electro-pneumatic system using Pulse-Width-Modulation (PWM) techniques and Fuzzy Logic controller

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Abstract. The main objective of this paper is to design a low cost electro-pneumatic module which can be used in the industrial automation equipment’s, robotic systems and mechatronic applications. Electro-pneumatic module includes four low-cost on/off solenoid valves and double acting cylinder. A Pulse width modulation (PWM) technique was used, which enable the model to correct the control of piston position and then to enable the system to follow the required trajectories accurately in many applications. Thus, it can be a good alternative at a lower cost than the using of proportional valves in the electro-pneumatic applications. A Fuzzy logic algorithm with PD control on the model in Matlab/Simulink environment to adjust the control values was applied. The simulation results and response of model were compared with the results from a previous practical with the similar model and controller but with a proportional valve. Finally, the simulation results showed a good accuracy with the practical results.

Keywords: Electro-pneumatic; Fuzzy Logic; PD control; Pulse width modulation (PWM); solenoid valves.

1. Introduction
The modern industrial applications require that the human works in different environments operation ranging from the industrial, nuclear, surgery to space exploration...etc. These environments may be highly risk to the humans and it is difficult to reach, or tiring and boring operations, in addition to the thermal or radiological environments that limits from the presence and work of human. But the automation systems and the robotic systems had enabled the humans to works in these environments without need to presence of connection or direct human presence, and these leads to a significantly reduce in humans accidents [1]. So, at present in the many industrial applications, the most of human workers are replaced by automation systems or robotic systems.

From the above, it found that the robotic systems and automation systems are an ideal solution for the many problems and difficulties in different fields.

Nowadays, the electro-pneumatic actuators have become an important component in robotic systems and industrial automation systems and widely used in these fields.
These electro-pneumatic actuators offer a lot advantages compared with the others actuators, where this type of actuators can to combine between the advantages and benefits for two types of actuators are the pneumatic and electrical actuator. The pneumatic system in the magnetic and electrical fields is considered an inert, so, this feature has made the pneumatic actuator use in many critical applications. In addition to that, this system is characterized by simplicity, reliability and cleanliness, with the low costs in configuration, work, maintenance and safety, as well as it has the ability to work in environments of aggressive, and at extreme temperatures (low and high). While, the electric system can provide the ability to control in the elements of system and thus the ability to control in the positioning processes. However, the poor damping and large non-linear factors due to mechanical friction and highly air compressibility makes it difficult to control in the pneumatic systems, especially to precise control in the piston position [2, 3].

The electro-pneumatic systems have a widely application with the robotic systems as well as in the industrial automation field due to for characteristics that have been mentioned previously, but the positions identifying process remain the most important in these applications. For the positions identifying processes, the pneumatic valves use to control in air pressure inside the cylindrical chambers thus controls the positioning process. The control valves in electro-pneumatic system which used to control the flow of inputs (air) in the actuator can be classified into two common types. The first type is a proportional valve, which have a high control accuracy and linear behavior with functions operate as follows: the armature takes some position between the open and closed position entirely according to the electrical signal, and this considered is a very suitable for the most applications of industrial automation. But they are expensive because of their characteristics and its complex structure. A proportional valve represents the most expensive of the system components, where the proportional valve cost sometimes is close to the same cost of all other components in the system, this leads to reduce its use in some applications [4].

The solenoid valves (on / off) can be used instead of using the proportional valves because of these valves are very cheap, and by using these types of valves can be built and developed an electro-pneumatic system at low cost. But the mechanism work of this type of valves takes either the open position entirely or closed according to the electric driving, and this is not appropriate with the work requirements in the industrial automation field and its applications. To overcome of this problem, a Pulse Width Modulation (PWM) technique is used, where that the PWM technique allows to systems using the solenoid valves to have a similar behavior to the behavior of systems that using a proportional valve but at much lower costs[5,6]. The method used to control and to overcome from the difficulties in electro-pneumatic systems depend on the artificial intelligence techniques. Where use fuzzy logic, which is one of the artificial intelligence techniques branches, and the fuzzy logic can to adjust the system parameters automatically and improve the performance of system elements. In this search fuzzy PD controller is applied on the model in Matlab/Simulink environment for the purpose to control and adjust the values of electro-pneumatic system [7,8].

2. Modelling of electro-pneumatic system

The pneumatic systems can be modeled mathematically using the following differential equations: equation of motion, through this equation can be describe the piston load dynamics, forces balance, friction compensation, two equations for the rate of pressure change in the single chambers, equation of the solenoid valves dynamics and standard equation for the mass flow.

The equation of motion for the piston rod load was derived according to the Newton’s second law and can be expressed as shown in Eq.1

\[
(M_L + M_p) \ddot{x} + \beta \dot{x} + F_l + F_{le} = P_1A_i - P_2A_2 - P_3A_3,
\]

Where:
\( \dot{\chi} \) – piston acceleration; ML – is the external load mass; MP – mass of piston and rod; \( \dot{x} \) – piston velocity; \( \beta \) – coefficient of viscous friction; \( F_f \) – friction force; FL – the external force; P1&P2 – are the pressure inside the behind and front chambers respectively; \( P_а \) – absolute ambient pressure; A1&A2 – are the piston area in the behind and front chambers respectively; \( A_r \) – is the cross-sectional area of the rod; Ps – the supply pressure\[9\].

The change of pressure rate for the behind and front chambers are presented in the Eq.2 and 3.

\[
\dot{P}_1 = \frac{RT}{V_{01}+A_1x} (\bar{m}_{in}\alpha_{in} - \bar{m}_{out}\alpha_{out}) - \alpha \frac{\pm A_1 P_1}{V_{01}+A_1x} \dot{x}
\]

\( x \) – piston velocity; \( \alpha_{in} = 1.4, \alpha_{out} = 1; \alpha = 1, 2; L \) – stroke length of the cylinder; \( V_1, V_2 \) - inactive cylinder volume for the behind and front chambers respectively; A1, A2- effective piston area of cylinder for the behind and front chambers respectively.

The standard equation for mass flow rate\( (\bar{m}_v) \) through the orifice of the effective area for solenoid valves\( (A_v) \) can be written as in Eq. 4 [10.11].

\[
\bar{m}_v = \begin{cases} 
C_f * A_v * C_1 * \frac{P_u}{\sqrt{T}} & \text{if } P_d \leq P_{cr} \\
C_f * A_v * C_2 * \frac{P_u}{\sqrt{T}} \left( \frac{P_d}{P_u} \right)^{\frac{1}{K}} \sqrt{1 - \left( \frac{P_d}{P_u} \right)^{\frac{k-1}{k}}} & \text{if } P_d > P_{cr}
\end{cases}
\]

Where:
\( \bar{m}_v \) – mass flow rate through the solenoid valves orifice; \( C_f \) – discharge coefficient, non-dimensional; \( P_u \) – upstream pressure; \( P_d \) – downstream pressure; \( P_{cr} \) – is the critical value of pressure =0.528; \( C_1, C_2 \) – constant coefficients; \( K \) – is the specific heat ratio.

In this system, four of low-cost on/off solenoid valves \( (2\times 2) \) were used as a command elements for the pneumatic system, and the effective area \( (A_v) \) for solenoid valves determine by using Eq 5.

\[
A_v = d^2 \frac{\pi}{4}
\]

Where: \( d \) = diameter of the solenoid valves[5].

The electro- pneumatic system proposed and modeled in this paper is shown in Fig.1
2.1. Pulse Width Modulation (PWM) technique

The pulse width modulation (PWM) technique is used to approximate or obtain to the required signal (multi-level or continuous) for real binary signals, a key point to operate the many devices used in various fields. The principle of PWM, as the name indicates, it is the change of signal pulse width. When using the technique of pulse width modulation, the signal frequency and capacity remain constant. The PWM signal can be achieved by comparing the continuous control signal (Vc) with the high frequency carrier wave (Vd), as shown in Fig. 2 (a and b) [12,13].

![Concept of PWM modulation Signal](image)

Figure 2. Concept of PWM modulation Signal

The mathematical description of the PWM signal can be given by the following relation:

\[
U_{PWM}(t) = \begin{cases} 
U_p & \text{for } V_c(t) \geq V_d(t) \\
0 & \text{for } V_c(t) < V_d(t) 
\end{cases}
\]

Where:

- UPWM – input voltage (signal),
- \(U_{PWM}(t) = \begin{cases} 
Up & \text{– switch is open} \\
0 & \text{– the switch is off} 
\end{cases}\)

2.2. Fuzzy Logic controller

The controller system is designed and achieved according to the fuzzy logic controller. A fuzzy logic controller was chosen because existence of many independent variables that effect on the behavior of electro - pneumatic system such as (temperature, damping and large non-linearity due to mechanical friction, high air compression and cylinder vibrations, etc.). Thus, the fuzzy logic seems enough to solve the control problem in the electro-pneumatic systems, this is because of the fuzzy logic is a very flexible and strong tool for dealing with the systems it have properties like inaccurate data, incomplete mathematical models and non-linearity behaviors, through this controller getting the minimum error in position and good behaviours of electro-pneumatic systems [14,15].

3. The mathematical modelling of Electro-pneumatic Module with fuzzy PD controllers and PWM

The modelling of system is an important step for any form of the control systems design, where the modelling helps to understand the system requirements. Through using the modelling and numerical simulations, good information on the dynamic behavior of system can be obtained before it is actually perform. As above mentioned, the data derived from modelling helps end users to determine their requirements, development the system to meet these requirements and design a good and efficient controller with high durability and accuracy.

The fuzzy logic controller of PD with pulse width modulation (PWM) were developed and tuned by Simulink Toolbox of Matlab-Simulink package, which depends on the piston motion equations of pneumatic cylinder, rate of the pressure change in the cylinder cavities and the mass of air flow rate. This model have a two inputs are the error (e) and error change rate (de), and the output is the position of pneumatic cylinder piston (x). Seven memberships functions are used in this design and Table 1 shows the full database of fuzzy logic rules.
Table 1. Rule base of fuzzy logic PD controller

|   | N_B | N_M | N_S | Z   | P_S | P_M | P_B |
|---|-----|-----|-----|-----|-----|-----|-----|
| N_B | N_B | N_B | N_B | N_B | N_B | N_B | N_B |
| N_M | N_B | N_B | N_B | N_B | N_M | N_M | N_S |
| N_S | N_B | N_M | N_S | N_S | Z   | N_S | P_S |
| Z   | N_B | N_M | N_S | N_S | P_S | P_M | P_B |
| P_S | N_S | P_S | Z   | P_S | P_S | P_M | P_B |
| P_M | Z   | P_S | P_M | P_M | P_B | P_B | P_B |
| P_B | P_B | P_B | P_B | P_B | P_B | P_B | P_B |

The model is developed using a pulse width modulation technique (PWM), the input signal for each solenoid valve is the voltage of pulse width modulation (PWM). The signal frequency in this model was 50 Hz, this means that the solenoid valves open and close every 20 ms at running. Therefore, through the solenoid valves that control by PWM, a multi-functional electro-pneumatic system can be developed at an appropriate price and good performance. Fig.3 shows a block diagram of the PWM in Simulink Toolbox of Matlab-Simulink package. Fig. 4 shows the comparator generates a modulated PWM signal. The simulation was carried out using the following parameters for the MP-9C pneumatic robot manipulator are: piston stroke - 0.15 m, piston diameter - 0.042 m, rod diameter - 0.022 m. The piston motion was controlled by 4 solenoid valves of type (2/2).

![Figure 3. Block diagram of the PWM in Simulink Toolbox of Matlab-Simulink package](image1)

![Figure 4. Generation PWM Signal](image2)

The schematic diagram of the electro-pneumatic system model connected with Fuzzy PD in the MATLAB-SIMULINK, which using the Eq.6 as shown in Fig.5

\[ u(k) = K_p \cdot e(k) + K_D \cdot \frac{de(k)}{dt} = K_p \cdot e_p(k) + K_D \cdot e_D(k) \]
Figure 5. Schematic electro-pneumatic fuzzy PD controller with PWM

Figure 6 shows the membership functions of the input variables \(e\) and \(de\), and Figure 7 shows the membership function of the output variable \(x\).

Figure 6. Error input membership function for

Figure 7. Position input membership function

4. Results

After the modelling and simulations for the electro-pneumatic model based on PWM which controlled by the fuzzy PD at different strokes, the model results showed that the control strategy presented is a good and stable enough as shown in Figures 8 (a) and (b).

Figure 8. Pneumatic cylinder displacement of controller fuzzy PD with PWM for (a) stroke of 0.15 m, (b) stroke of 0.08 m

These figures represent the model results with a fuzzy PD based on PWM during the stroke 0.15 m and during the stroke 0.08 m, respectively.
The model results are compared with the results taken from [16], for a similar model using the same of controller unit but with a proportional valve. It was found that the results were a good and very close as shown in Table (2).

Table2. The comparison of positioning errors for the model results and the results of previous experimental work

| Stroke, (m) | Position errors of fuzzy PD, (Experimentally results) | Position errors of fuzzy PD, (Simulations results) | Percentage Error |
|------------|--------------------------------------------------------|--------------------------------------------------|-----------------|
| 0,15       | 0,00052                                                | 0,00054                                          | 2·10^{-5}       |
| 0,14       | 0,0005                                                | 0,00052                                          | 2·10^{-5}       |
| 0,12       | 0,00048                                                | 0,0005                                          | 2·10^{-5}       |
| 0,1        | 0,00046                                                | 0,00050                                          | 4·10^{-5}       |
| 0,08       | 0,00044                                                | 0,00047                                          | 3·10^{-5}       |

5. The discussion and Conclusions
The model of the electro-pneumatic system was proposed, designed and developed in this search. This model includes a double acting pneumatic cylinder with four cheap (2/2) on–off solenoid valves. As it is known, the solenoid valves works only in the opening and closing position, this is not suitable for applications in the modern industrial systems in general and mechatronic systems in particular. Therefore, to enhance the behaviour of solenoid valves and obtain on a similar behaviour to the proportional valves behaviour used in electro-pneumatic systems, the PWM technique was proposed and used. In this search, the PWM technique work at 50 Hz frequencies with pressure 5 bar. To obtain the required piston position for the system, the fuzzy PD controller was used. The response and results were a good as shown in figure (9), and very close when compared it with the results from the previous practical [16] for a similar model use the same of controller unit but with a proportional valve. Where the difference was very little, about (2·10^{-5} ~ 4·10^{-5}), and as shown in table 2.

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