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OPTIMAL INTERVAL TYPE-2 FUZZY LOGIC CONTROLLER FOR PNEUMATIC SERVO ACTUATOR SYSTEM

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Abstract

In this paper, the positioning of the pneumatic servo actuator system is controlled by the interval type-2 fuzzy logic controller (PD-like IT2-FLC). The main goal of the proposed design is to assure and accommodate the nonlinear system and the uncertainty in its parameters. Therefore, these challenges consider verifying the efficiency and effectiveness of the proposed controller. The optimal parameters of the controller are obtained by the cultural algorithm (CA), which is one of the effective optimization algorithms. The simulation results show that the proposed optimal controller can achieve a desirable specification and guarantee the robustness of stability and performance in the presence of uncertainty and disturbance. Moreover, the results show a desirable performance in terms of obtaining smooth and unsaturated state voltage control action that stabilizes the pneumatic servo actuator system and minimizes the position tracking error of the system output. An improvement of 20% is achieved using the proposed controller in compared the previous controller.

Keywords: Cultural algorithm, Interval type-2 fuzzy logic controller, Nonlinear-control, Optimal control, Pneumatic servo actuator system.

1. Introduction

The pneumatic actuator system is widely used in the automation and robotics industry more than electrical and hydraulic actuators because it is easy to maintain, clean, safe, cheap, and lightweight. In addition, it provides a high degree of compliance and low implementation cost [1-5]. Furthermore, it has good performance in terms of accuracy, robustness, and stability. However, previous researchers found that the system has non-linearity and friction forces due to the air compressibility and the variation in thermodynamic conditions due to uncertainty in a number of system parameters [6].

The study of the pneumatic actuators has become aggressive since the 1950s, where Prof. J. L. Shearer in 1956 was the first developer to work on pneumatic control systems [7]. In the literature, for pneumatic positioning systems, many different controller designs are explored. Typically, the conventional controllers are not sufficient for the pneumatic actuators because of the nonlinearities and uncertainties. Therefore, it is difficult for conventional controllers to be implemented in the pneumatic actuator systems [8]. Based on previous studies, some of the most popular controllers used in the systems include the sliding mode controller (SMC), the proportional integral derivative (PID), and the adaptive controller, which were used to achieve accurate position control. Varseveld and Bone proposed a conventional PID controller with bounded integral, friction compensation, and position feed-forward. The purpose of the employed control techniques was to control the friction force, reduce the steady-state error, and reduce the errors to ram and S-curves, respectively [9]. The proposed controller with the techniques improved the performance of the actuator but the accuracy of steady state or/and the rise time was/were unaffected.

The PID controller combined with velocity feed-forward (PIDVF) was proposed by Saleam, et al. [10]. The PIDVF was applied to obtain the friction parameters before applying it to the physical system. Takosogly, et al. had used a fuzzy logic type-1 with a proportional derivative (PD) controller to design positioning control for the pneumatic servo system [11]. The simulation result was enhanced, but unfortunately, the numerical solution becomes complex. According to some researches, a nonlinear PID was proposed with other different control strategies, by [12, 13], in 2014 and 2015, namely self-regulation (SN-PID) and multi-nonlinear (MN-PID). The results showed no improvement when compared to NPID. Song and Ishida designed a robust sliding mode controller based on the structural properties of the pneumatic servo system and the theory of Lyapunov stability [14]. However, the proposed controller was only applied to the second-order system.

In 2017, two different approaches were presented by Hidalgo and Garcia for SMC to reduce the effect of control valve friction [15]. The first approach was the integration of SMC under an external topology with different sampling times to control the flow of the plant. The second approach SMC acts as a slave control loop for the valve position stem while the PI controller acts as a master control loop. The experimental result showed a chattering problem. An adaptive fuzzy-PD controller was proposed to improve the friction compensation with a focus to enhance the accuracy of pneumatic servo position control systems [16]. The controller was applied to the system without any effect of load. Therefore, it was ineffective with a load. The model reference adaptive controller (MRAC) was suggested by Zhu and Barth [17]. The suggestion focused on the compensation frication and payload in a servo pneumatic actuator system, which are the most commonly occurred in the mechanical system. The response of the system with the controller had such a long rise time. The two types of fuzzy logic control (FLC) rules to design an integral sliding mode control (ISMC) were proposed by Azahar, et al. [18]. The proposed controller used two rules of fuzzification to reduce the position error but couldn't eliminate the overshoot [18].

In this paper, a new design of fuzzy logic controller of type-2 has been proposed for nonlinear and uncertain pneumatic servo actuator systems, using culture algorithm optimization to obtain the parameters of the controller. The results showed the best performance in terms of rising time, overshoot, settling time, and steady-state error. The formulated fuzzy type-2 is stable, productive, and able to reject disturbances. The paper is organized as follows: Section 2 presents the pneumatic servo actuator system model, and the design of the fuzzy logic controller type-2 will be presented. The results and discussion are shown in Section 3. Finally, the conclusion is given in Section 4.

2. Materials and Methods.

2.1. The pneumatic servo actuator system model.

The system of pneumatic actuators can be modelled by using several methods such as system identification or theoretical mathematical analysis. The researchers used the most common, which is a mathematical analysis to model the pneumatic actuator. The requirements to structure a mathematical model need to combine thermodynamics, motion dynamics, and fluid dynamics. Moreover, three major factors must be involved: I) the pressure, the temperature of the air in the cylinder and volume, II) the mass flow rates, III) the loaded dynamic [19]. Figure 1 shows a schematic of the pneumatic servo actuator.

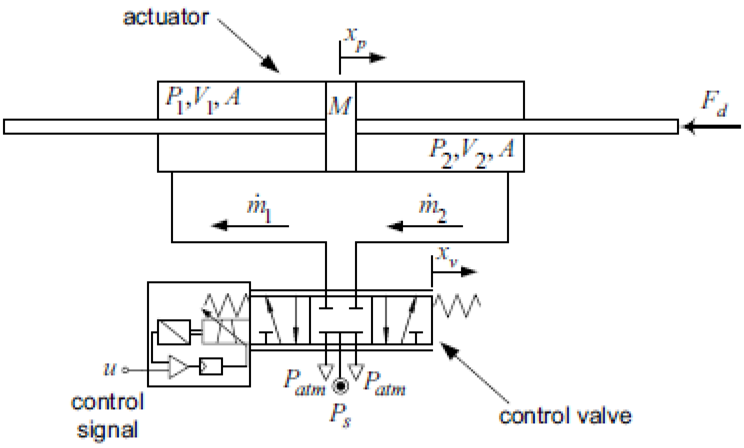

Fig. 1. Schematic of a typical valve controlled pneumatic actuator [20].

The dynamic system can be described in the following nonlinear state equations [20]:

$$\dot{x}_p = v_p \quad (1)$$

$$\dot{v}_p = \frac{1}{M}(-bv_p + AP_1 - AP_2 - F_d) \quad (2)$$

$$\dot{P}_1 = \frac{\gamma RT}{V_1}\,\dot{m}_1 - \frac{\alpha\gamma RT}{V_1}\,\dot{x}_p \tag{3}$$

$$\dot{P}_2 = \frac{\gamma RT}{V_2}\,\dot{m}_2 - \frac{\alpha\gamma RT}{V_2}\,\dot{x}_p \tag{4}$$

$$\dot{x}_v = -\frac{1}{\tau_v}\,x_v + \frac{k_v}{\tau_v}\,u \tag{5}$$

where x_p is the position of the actuator, v_p is the velocity of the actuator, M represents the mass of piston and external load, b is the viscous friction coefficient, A is the annulus area of the piston, and F_d is the disturbing force. P_1, P_2, V_1, and V_2 are the instantaneous absolute pressures and volumes in each chamber, respectively. The parameters γ, R, T and α are the ratio of specific heats, the ideal gas constant, the temperature of the air source, and compressibility flow correction, respectively. x_v is the displacement of the valve spool, τ_v represents the time constant of the control valve, k_v represents the value spool position gain and u is the control signal [20].

The equation of nonlinearity that governs the air mass flow rate through each control valve orifice is [21].

$$\dot{m} = \begin{cases} \frac{C_1 K_f x_v P_u}{\sqrt{T}} & \frac{P_d}{P_u} \le P_{cr} \\ \frac{C_1 K_f x_v P_u}{\sqrt{T}} \sqrt{1 - \left(\frac{P_d/P_u - P_{cr}}{1 - P_{cr}}\right)^2} & \frac{P_d}{P_u} > P_{cr} \end{cases} \tag{6}$$

where $C_1 = \sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}$

The P_d and P_u represent the absolute downstream and upstream pressure, respectively. K_f is the valve gain and P_{cr} is the critical pressure ratio, which is taken as 0.2 by Sanville [21].

Taylor series expansion was used to linearize Eq. (6) about the operating point o, neglecting 2nd and higher-order terms as well as any control valve leakage. In each chamber, the mass flow can be written as follows [20]:

$$\begin{aligned} \Delta\dot{m}_1 &= C_{f1}\Delta x_v - C_{p1}\Delta P_1 \\ \Delta\dot{m}_2 &= C_{f2}\Delta x_v - C_{p2}\Delta P_2 \end{aligned} \tag{7}$$

where Δ indicates a perturbation from the operation point value, e.g. $\Delta x_v = x_v - x_{vo}$. Parameters C_{f1} and C_{f2} are the value flow gain. C_{p1} and C_{p2} are flow-pressure coefficients.

Substituting Eqs. (1) and (5) in Eq. (7), the transfer function model of the open-loop system, for the position of the actuator, can be written as follows [20]:

$$X_p(s) = G_s(s)\,G_d(s)U(s) - G_d(s)F_d(s) \tag{8}$$

where

$$G_s(s) = \frac{\gamma RT k_v A C_{f1}(\gamma RT C_{p2} + V_2 s)}{(\tau_v s+1)(\gamma RT C_{p1} + V_1 s)(\gamma RT C_{p2} + V_2 s)} + \frac{\gamma RT k_v A C_{f2}(\gamma RT C_{p1} + V_1 s)}{(\tau_v s+1)(\gamma RT C_{p1} + V_1 s)(\gamma RT C_{p2} + V_2 s)} \tag{9}$$

and

$$G_d(s) = \frac{(\gamma RT C_{p1} + V_1 s)(\gamma RT C_{p2} + V_2 s)}{E(s)} \tag{10}$$

with

$$E(s) = s(Ms + b)(\gamma RTC_{p1} + V_1 s)(\gamma RTC_{p2} + V_2 s) + \propto \gamma A^2 s[\gamma RT\,(P_1 C_{p2} + P_1 C_{p2}) + (P_1 V_2 + P_1 V_1)s] \quad (11)$$

Table 1 defines the parameters of the model and the range of values that were used in the controller. Proportional flow control valve and a double-rod actuator with 500 mm stroke [20].

Table 1. List of nominal modal parameters and their ranges [20].

Uncertain Parameter	Symbol	Value			Unit
		min	nominal	max	
Load mass	M	1.81	1.91	2.01	kg
Ideal gas constant	R	-	287	-	J/kg.K
Temperature of air source	T	-	300	-	K
Piston annulus area	A	-	10.6	-	cm^2
Viscous damping coefficient	b	60	70	80	N.s/m
Value spool position gain	k_v	-	0.25	-	mm/V
Value time constant	τ_v	3.6	4.2	5	ms
Value spool displacement	x_{vo}	0	0	0.125	mm
Ratio of specific heats	γ	-	1.4	-	-
Pressure-volume work correction factor	α	-	0.89	-	-
Chamber pressure	P_1	3.7	3.7	4.5	bars
Chamber pressure	P_2	2.3	3.7	3.7	bars
Chamber volume	V_1	1.32	2.64	3.96	$m^3 \times 10^4$
Chamber volume	V_2	1.32	2.64	3.96	$m^3 \times 10^4$
Flow gain	C_{f1}	8	13.6	13.6	kg/s.m
Flow gain	C_{f2}	8	13.6	13.6	kg/s.m
Flow-pressure coefficient	C_{p1}	0	0	2	kg/Pa.s
Flow-pressure coefficient	C_{p2}	0	0	2	kg/Pa.s

$G_c(s)$ represents the proposed controller, whereas $G_s(s)$ and $G_d(s)$ refer to transfer functions of the plant in (9) and (10). So, the response of the closed-loop system can be written as:

$$X_p(s) = \frac{G_c(s)G_s(s)G_d(s)}{1 + G_c(s)G_s(s)G_d(s)} X_d(s) - \frac{G_d(s)}{1 + G_c(s)G_s(s)G_d(s)} F_d(s) \quad (12)$$

2.2. Controller design

It is desirable to synthesize a controller that can stabilize the pneumatic servo actuator. This can be achieved by employing an interval type-2 fuzzy logic controller (IT2 FLC), which requires linearizing the nonlinear system around the operating point. Although the design of the controller is based on the linear model it can cope with uncertainties. The IT2 FLC will be utilized to enhance the system performance by eliminating the error and the oscillation.

2.2.1. Interval type-2 fuzzy logic controller (IT2 FLC)

The IT-2 FLC has been proposed to deal with the influence of uncertainties and external and internal disturbances. Figure 2 shows the structure of IT2 FLC, which is quite similar to the structure of interval type-1 fuzzy logic controller (IT-1 FLC).

In general, it will not change for any type-n, but the number of types refers to the degree of fuzziness [22]. There are three main differences between them I) the higher dimensional membership functions, which has an extra dimension to express the uncertainties magnitude II) the uncertainty footprint, which is the area between lower and upper membership functions shown in Fig. 3 [22] III) the requirement of the type-reduction in the defuzzification stage due to the higher-order fuzzy logic in the fuzzification stage [23].

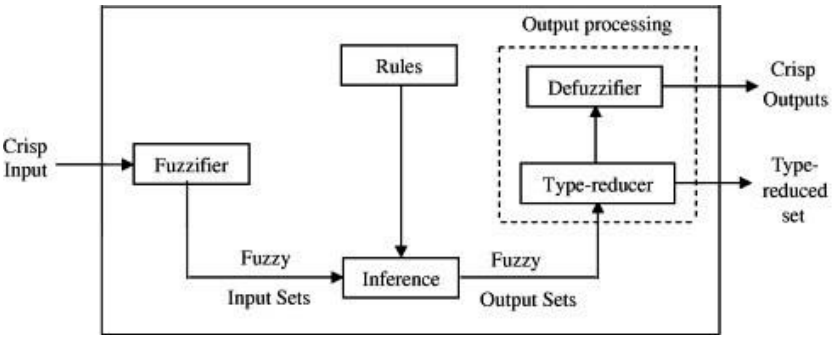

Fig. 2. IT-2 FLC system structure [21].

The IT2 FLC consists of four main components; fuzzifier, inference engine, rule base, and output processing, and it works as follows [22]: the crisp input is the first fuzzified into input IT-2 FLC. Then, the input will activate the inference engine and the rule base (Rules) will produce the output of the IT2 FLC. The IT2 FLC rules will be the same as in IT1 FLC, but the consequent and/or the antecedents will represent in IT2 FLC. Then, as a last step, the output processing will combine the output sets and type-reducer sets. After that the type-reduced sets will be defuzzified to obtain crisp outputs.

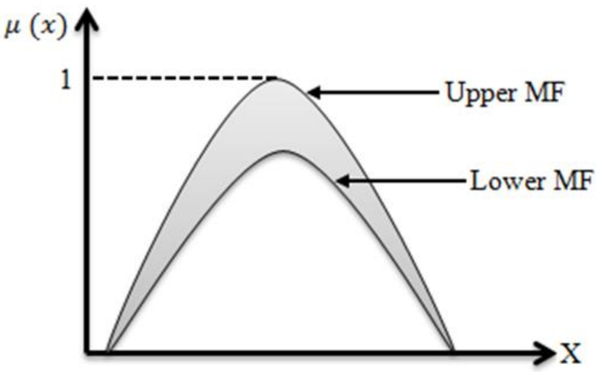

Fig. 3. An example of the upper and lower memberships functions.

By considering the principle knowledge base expressed as 'If…then", statements in the rule base block IT2 system will have rules (Q) in general form [23]:

$$Ru^Q\colon \boldsymbol{IF}\ x_1 is\ D_1^Q and\ \ldots\ldots\ldots and x_i is\ D_i^Q\ \boldsymbol{THEN}\ z\ is\ Z^Q \quad (13)$$

where D_I^Q $(I = 0, \dots\dots, i)$ terms are modelled by IT-2 fuzzy sets, and Z^Q represents the interval bounded by the upper and lower consequence$\left[\underline{Z}^Q, \overline{Z}^Q\right]$.

The interval of firing $\left[\underline{f}^Q, \overline{f}^Q\right]$ is calculated by combining the input intersection with the lower MF $\underline{\mu}_{F_i^Q}(x_i)$ and upper MF$\overline{\mu}_{F_i^Q}(x_i)$ and the antecedent rules [23].

$$\underline{f}^Q = \underline{\mu}_{F_1^Q}(x_1) \times \underline{\mu}_{F_2^Q}(x_2) \times \dots\dots\dots\dots \times \underline{\mu}_{F_i^Q}(x_i) \tag{14}$$

$$\overline{f}^Q = \overline{\mu}_{F_1^Q}(x_1) \times \overline{\mu}_{F_2^Q}(x_2) \times \dots\dots\dots\dots \times \overline{\mu}_{F_i^Q}(x_i) \tag{15}$$

Before performing the defuzzification process, the IT2 fuzzy sets reduce in order. This can be accomplished by combining the consequent of the corresponding rule with the firing interval (type-reduction algorithm). Centre-of-sets is the most common method used in type reduction. Finally, the output can be calculated by using the following expression.

$$z = [z_r, z_l] = U_f \frac{\sum_{q=1}^{Q} f^q z^q}{\sum_{q=1}^{Q} f^q} \tag{16}$$

The z_r and z_l can be found by

$$z_r = \frac{\sum_{q=1}^{R} \underline{f}^q \overline{z}^q + \sum_{q=R+1}^{Q} \overline{f}^q \overline{z}^q}{\sum_{q=1}^{R} \underline{f}^q + \sum_{q=R+1}^{Q} \overline{f}^q} \tag{17}$$

$$z_l = \frac{\sum_{q=1}^{L} \overline{f}^q \underline{z}^q + \sum_{q=L+1}^{Q} \underline{f}^q \underline{z}^q}{\sum_{q=1}^{L} \overline{f}^q + \sum_{q=L+1}^{Q} \underline{f}^q} \tag{18}$$

where $\overline{f}^q$ and $\underline{f}^q$ are the grades of the firing strength that correspond to the most points left and right. R and L represent the switching points (the changing from lower membership grades to the upper membership grades and vice versa). In this research, the Karnik-Mendel algorithm (KM) procedure has been used to find and calculate the switching points for both right and left points [24]. The defuzzification can be found by taking the average value of z_r and z_l. Thus, the defuzzified crisp output value becomes

$$z_{def} = \frac{z_r + z_l}{2} \tag{19}$$

Figure 4 shows the basic design of the PD like IT2 FLC. It is clear to see the error signal and derivative of the error signal feed the IT2 FLC system as a PD-like fashion. Then, the controller action can be achieved by multiplying the IT2 crisp output by a gain.

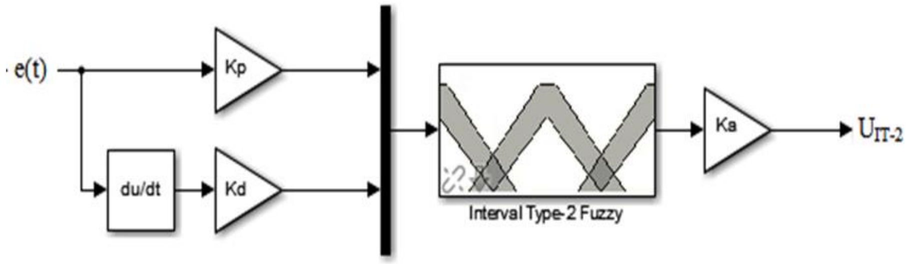

Fig. 4. PD like IT2 FLC.

For this pneumatic servo system, in the fuzzifier block, there are three Gaussian-shaped membership functions that are implemented. The corresponding of each membership function has three certain levels (Low, Medium, and High). In general, there is no rule to select the shape of memberships, but the response of the system was better with the Gaussian-shaped membership function.

In this work, three-level input variables are used to utilize fast and reliable results. Since the error and its derivative are supplied on the IT2 FL system, two identical fuzzifiers are used. While the design of the rule-base system was based on the error behavior exhibited in Table 2,

Table 2 shows the standard Rule-base which is used to minimize the error signal and its derivative. The Takagi-Sugeno-Kang (TSK) model was used in the execution of defuzzification, which means that the value of the FL output is a crisp value with a level L demonstrated in the table of rule-base. The reason to use the TSK model in the defuzzification is to prevent the encroachment of the output limits, which is the most common problem in the defuzzifiers type of Mamadani.

Table 2. The rules of IT-2 FL system.

$\dot{e}/e$	Low	Medium	High
Low	L_1	L_2	L_3
Medium	L_2	L_3	L_4
High	L_3	L_4	L_5

2.2.2. Controller parameters tuning

In this research, the Cultural Algorithm (CA), which represent one of the most effective optimization algorithms, has been used to obtain the parameters of the proposed controller. The base of CA is a cultural evolutionary process [25]. The process has two levels to the evolution of a micro and macro evolutionary level. The individuals' behavior traits can be described socially as acceptable or unacceptable, which will be at the micro evolutionary level. The individuals' ability transfers their experience to the next generation that will be at the macro evolutionary level [26]. The CA consists of a population and a belief space. Therefore, it is known as dual inheritance evolutionary. The evolutions process is directly used in the population space and the belief space will save the acquired knowledge. The problems of the population will be solved by using belief space [25, 26]. The following steps were used to design the interaction between them [26]:

A- An initial population *p* candidate solution will be selected for each one of the parameters, a uniform distribution gives domain from 1 to *n*.

B- The performance of each parameter will be assessed by an objective function f.

C- The candidate solutions and problem domain will initialize the belief space.

D- New offspring solutions (*p*) will be generated by applying a variation operator (*V*). Now, there are 2p.

E- The performance of each offspring will be assessed by the objective function f.

F- Competitions (*c*) for each individual will be randomly selected from the population of size 2p.

G- The great p solutions will be selected to be parents for the next generation.

H- The belief space will be updated by acceptance function and accepting individuals.

I- Available time exhaust goes back to step D, or unless an acceptable solution is found.

The target of CA was formulated to design an optimal IT2 FLC with the following requirements:

i. Eliminate the error steady-state.
ii. Eliminate the system oscillations.
iii. Minimize the IT2 FLC cost function by obtaining suitable tuning for the parameters.
iv. Maximize the system gain and phase margin.

The above requirements can be combined in a single constraint to construct a new performance index for the proposed controller. This performance criterion can be expressed by:

$$J(h) = \int_0^{t_f} e(t)^2 dt \tag{20}$$

Figure 5 shows the block diagram of the complete control system. Since the objective of the IT2 FLC is to be implemented on position pneumatic servo system.

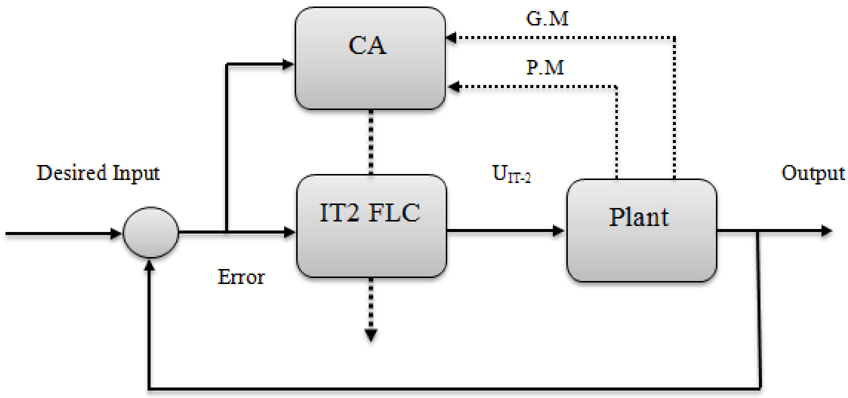

Fig. 5. System block diagram.

3. Results and Discussion

This section addresses the implementation of the proposed IT2 FLC along with the parameters of optimization technique by applying it into the nonlinear system. Figure 6 illustrates the behavior of the position of pneumatic servo actuator without controller. It is clear to see that the response of the system is unstable with high oscillation. So, the design of a suitable controller to subtilize the system and achieve a desired performance is required.

The Cultural Algorithm (CA) is being used to obtain the optimal values of the proposed controller. The procedure illustrated in the invasive CA optimization section is an M-file program that accepts the variable parameters as input and produces their optimal values, then it minimizes the error as an output. The developed program can access and analyse the SIMULINK model based on the provided performance measure. In this work, the error signal is the most significant element which is affected by tuning the controller parameters. Table 3 shows the values of parameters that have been used in CA to find the optimal values for the parameters of the proposed controller

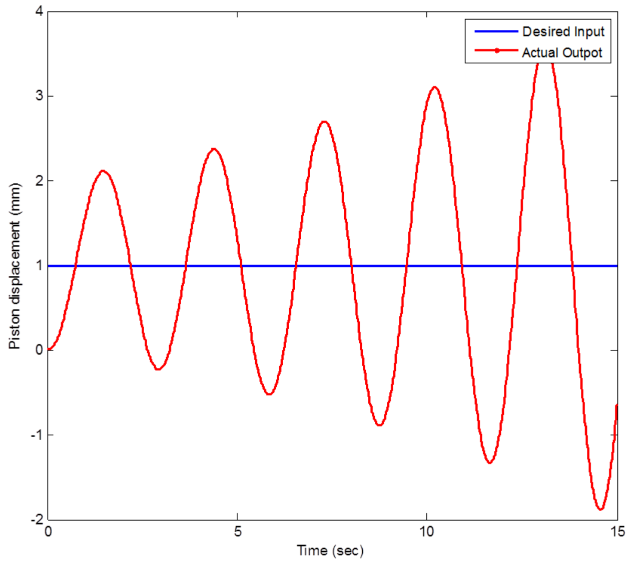

Fig. 6. The response of the system without controller.

Table 3. CA parameters values.

Parameter Name	Value
Beta	0.5
Alpha	0.3
Acceptance ratio	0.35
Population size	20
Maximum number of iterations	50
Number of decision variables	3
Decision variables lower bound	1
Decision variables upper bound	6

The evaluation of the best cost function value can be shown in Fig. 7, which was calculated by the cultural optimization algorithm. It is clear to see that the convergence of CA did not significantly improve the convergence above 40 iterations. Also, it is shown that a clear minimization in the cost function has been achieved using this optimization method.

Table 4 shows the optimized parameters (K_p, K_d and K_a) of the proposed controller that was obtained by using CA (offline).

We have contacted the optimization of the controller parameters using particle swarm optimization (PSO) and ant colony optimization algorithm (ACO), but since they have produced exactly the same results. We have not included in this research to reduce recurrence.

Figure 8 shows the response of the system when the optimal proposed controller has been applied. It is shown that the proposed controller could stabilize the system with zero steady-state error, and without overshoot. The signal of control action was less aggressive while maintaining an applicable range, as shown in Fig. 9. This means that the proposed controller gave an applicable content effort.

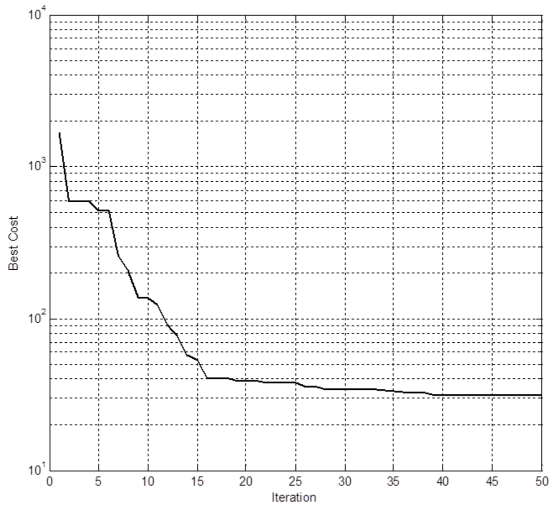

Fig. 7. Best cost vs. Iteration.

Table 4. The parameters of IT-2 FLC.

Parameter Name	Value
K_p	3.999
K_d	0.629
K_a	6.899

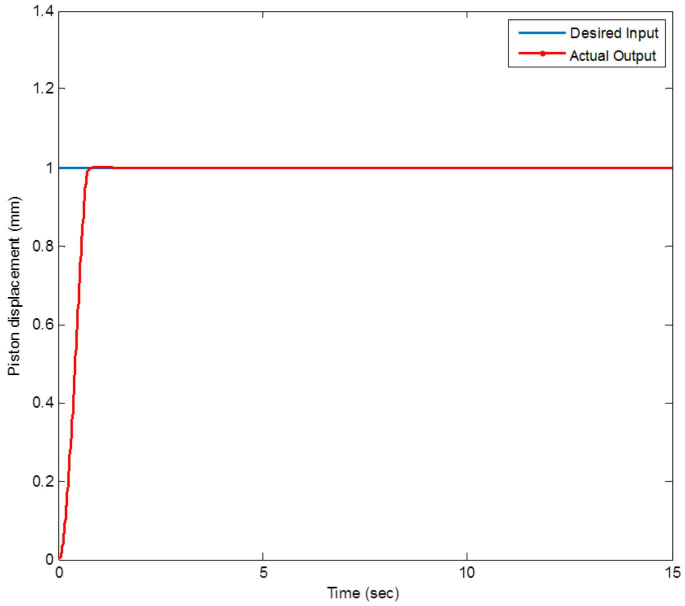

Fig. 8. The time response with PD-like IT2 FLC.

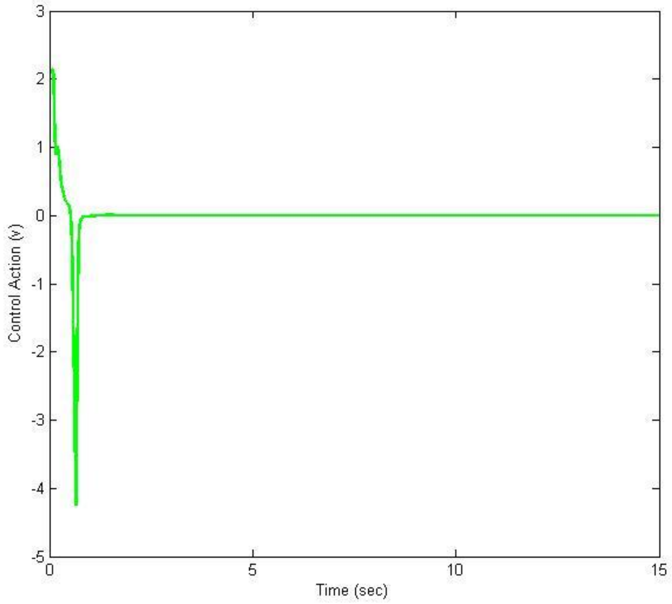

Fig. 9. The signal of control action.

Figure 10 shows the performance of tracking for the controlled system when the input signal is trajectory. It seen that the system can effectively track the desired trajectory. This behavior can clearly address the ability of the IT2 FLC in improving the dynamic behavior of the pneumatic servo actuator system **.**

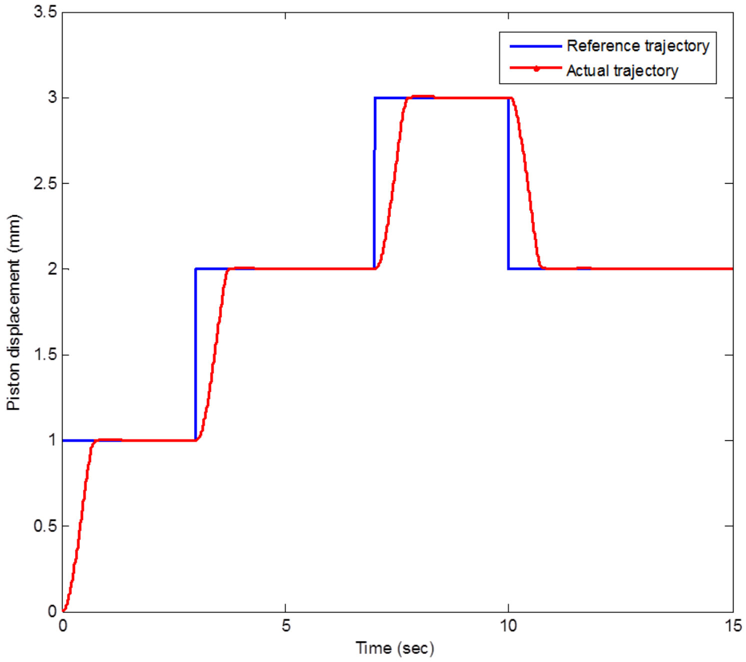

Fig. 10. Tracking properties of the controlled system with PD-like IT2 FLC.

A disturbance signal was subjected to the system to test the robustness of the controlled system. Its value was 15% of the desired input and it was applied to the system at t= 7 s. Figure 11 shows the effect of the disturbance on the system and how the IT2 FLC can effectively reject its effect by holding the system output on the steady-state value. Moreover, the control action behavior is shown in Fig. 12. It is shown that the proposed controller can effectively reject the subjected disturbance with minimum control energy.

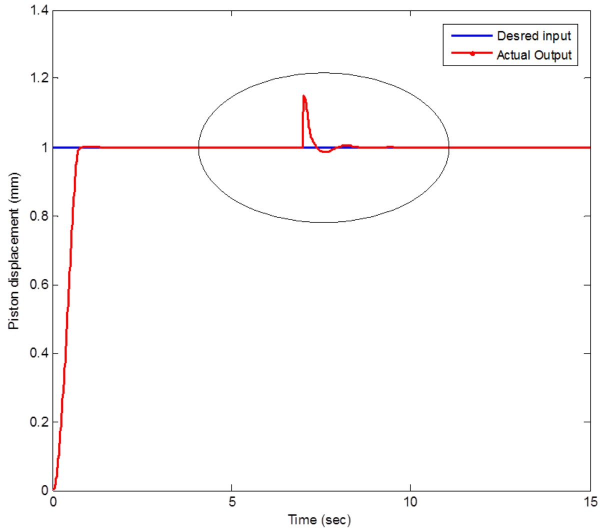

Fig. 11. Tracking and disturbance rejection properties of the controlled system.

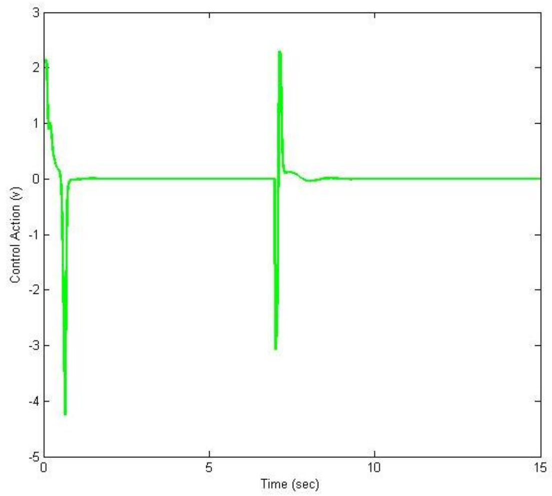

Fig. 12. Control action when the disturbance was applied to the system.

As another test for checking the robustness of the controlled system, a change in system parameters as in Table 1 is considered. Figure 13 shows the responses of the controlled system, which is obvious to see that the proposed controller has the capability to compensate the system parameters variation to keep the system stable, fast, with zero steady-state error. This means that the proposed controller is a powerful in compensating any variation in system dynamics. Also, it can be seen that the superiority of the proposed controller in achieving a more desirable time response specification.

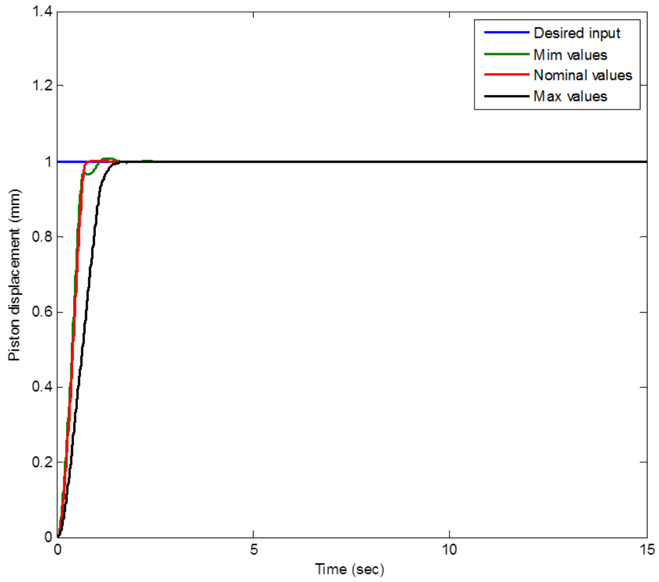

Fig. 13. Time responses specification of uncertain system parameters.

A comparison between the proposed IT2 FLC, IT1 FLC [16] and QFT controller [6, 26] for pneumatic servo actuator has been given to show the effectiveness of the IT2 FLC. Table 5 shows a comparison between them in terms of time response specifications. It is shown that, the IT2 FLC can achieve a desired performance with fast response in comparison to the IT1 FLC and QFT controller.

Table 5. Performance comparison.

Controller / Specification	IT2 FLC	IT1 FLC [16]	QFT [6, 27]
Rise time, t_r (s)	0.471	-	0.611 - 1.46
Settling time, t_s (s)	Less than 0.8	Less than 1	1.06 - 2
Overshoot, Mp	Without Mp	With Mp	-

4. Conclusion

In this paper, the interval type-2 fuzzy logic controller (PD like IT2FLC) was proposed to ensure the robustness specifications for the pneumatic servo actuator system with desirable time response specifications. Moreover, the designed controller has been utilized to overcome the nonlinearity of the system. The cultural algorithm method has been used as an effective optimization method in the design procedure to obtain the optimal parameters of the proposed controller. The results showed that the proposed controller succeeded in satisfying the robustness specifications for the pneumatic servo actuator system. Also, a more desirable performance was achieved in terms of tracking properties and disturbance rejection properties. An improvement of 20% is achieved using the proposed controller in compared the previous controller.

Nomenclatures

A	Piston annulus area, cm^2
b	Viscous damping coefficient, N.s/m
C_{fi}	Flow gain, kg/s.m
F_d	Disturbing force, N.m
k_v	Value spool position gain, mm/V
M	Load mass, kg
P_i	Instantaneous Pressures, bars
R	Ideal gas constant, J/kg.K
T	Temperature of air source, K
V_i	Volumes, $m^3 \times 10^4$
x_{vo}	Value spool displacement, mm

Greek Symbols

α	Pressure-volume work correction factor
γ	Ratio of specific heats

Abbreviations

CA	Cultural Algorithm
ISMC	Integral Sliding Mode Control
IT2 FLC	Interval Type-2 Fuzzy Logic Controller
KM	Karnik-Mendel
MRAC	Model Reference Adaptive Controller
PID	Proportional Integral Derivative
QFT	Quantitative Feedback Theory
SMC	Sliding Mode Controller
TSK	Takagi-Sugeno-Kang

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