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Fuzzy Controller Parameters Optimization Based Particle Swarm Optimization Algorithm for Electro-Hydraulic System

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ABSTRACT

Particle Swarm Optimization Algorithm (PSOA) has emerged recently as an efficient and powerful technique for the optimization of real parameters. The current study presents control scheme for electro-hydraulic actuator system which utilizes particle swarm optimization (PSO) for off-line tuning of the Fuzzy Proportional-Derivative (Fuzzy PD) controller. The gains and Membership Functions (MFs) tuned by PSOA which has been implemented depending on the performance indices: ITAE (Integral Time of Absolute Error), ISE (Integral Square of Error), and IAE (Integral Absolute of Error).

Keywords: Hydraulic system, Fuzzy inference systems, Particle Swarm Optimization (PSO), Position control.

الخلاصة: قد ظهرت مؤخرا خوارزمية أمثلية أسراب الطيور (PSO) باعتبارها تقنية فعالة وقوية لتحسين المعلمات الحقيقية. في هذه البحث تم تصميم مسيطر لنظام التشغيل الكهروهيدروليكي الذي يستخدم مبدأ أمثلية أسراب الطيور (PSO) من أجل تنغيم عناصر المسيطر والذي يكون من نوع التناسبي التكاملي الضبابي(Fuzzy PD). تم حساب عناصر المسيطر والتي تشمل كل من المكاسب ودوال الإدخال والإخراج لهذا النوع من المسيطر. هذه العناصر تم حسابها بالاعتماد على عدة دوال للهدف والتي تشمل كل من: ITAE (تكامل الزمن في القيمة المطلقة للخطأ)، ISE (تكامل مربع الخطأ)، IAE (تكامل القيمة المطلقة للخطأ)

1. INTRODUCTION:

Electro-hydraulic servo systems (EHSS) have a vital role in the new made up automaticity. It offers many advantages such as high torque and fast response characteristics precision positioning applications **Merritt [1]**. The EHSS applications include; paper machines, material test machines, molding machines, fatigue testing, ships, manipulators, injection robotics, and aircraft equipment. The drive of EHSS are extremely not linear because of the directive alteration of valve opening, abrasion, etc**. Soh and Bobrow [2]**.

The performance of checking out position of the so-called electro-hydraulic actuator are confirmed in case its sturdiness, and positioning rigor is ensured **Kastreve [3**].

Regarding position control algorithm parts that have to do with EHSS, traditional PID regulator is put in proper applications. A PID controller requires exact mathematical modeling of system which is controlled; the performance of the system is questionable if there is parameter variation **Ishak et al. [4]**. In the recent few years' research devoted to fuzzy logic and its application to EHSS has significantly developed. **Amanuel [5]** stated that, when he made and equated in the conventional PID regulator EHSS, the outcome of simulation proves that fuzzy PID control system has improved static and developing performance. In another study **Zupr [6]** the results revealed a different interbred-fuzzy control criterion for hydraulic servo actuator. Adaptability has been included by fuzzy logic regulator which is designed as a system for self-learning. Unfortunately, there has been no regular way to prove the junction of a learning mechanism and the whole constancy of the control system.

Nowadays there are many techniques like particle swarm optimization, Ant, Bee colony, Genetic, are used as optimization algorithms for improving the controller's performance by finding the optimized controller's parameters. **Daniel [7]** introduced a design of FLC related to EHSS with the abrasion and inner leakage joined in the system. The PSO algorithm has been used to change the scaling elements of the PI fuzzy controller; therefore, the controller proposed shows the assured sturdiness and positioning rigor.

In the current study, nonlinear mathematical model for the actuator has been modeled and simulated using MATLAB/SIMULINK. An intelligent position controller for EHSS has been designed with friction and investigated using Fuzzy Logic Controller (FLC). The FLC parameters are tuning by the algorithm of particle swarm optimization. The parameters that have been optimized are the antecedent and consequent membership functions, and the fuzzy inference system scaling factors.

2. MATHEMATICAL MODEL

Fig.1 depicts the physical model of the electro-hydraulic actuator considered in this study. This model consists of a double-ended hydraulic cylinder driven by a direct drive servo-proportional valve. The aim is to structure a fuzzy regulator to include accurate location regulator of the nonlinear electro-hydraulic servo system. **Merritt [1]** listed the differential equations governing the actuator dynamics for an ideal critical servo valve with a matched and symmetric orifice.

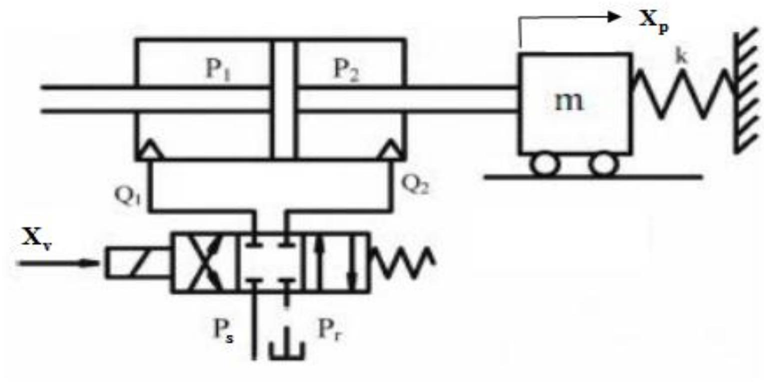

Figure 1. Electro-hydraulic system

The behavior of the spool position for the servo valve can be expressed as **R.G. et al. [8]**:

$$u = \frac{1}{k_v}\left(\frac{1}{w_v^2}\ddot{x}_v + \frac{2\zeta_v}{w_v}\dot{x}_v + x_v\right) \tag{1}$$

Where k_v is the gain of the servo valve, u is the control action (voltage), ζ_v and ω_v represent the damping ratio and the equivalent natural frequency of the servo valve, respectively.

The fluid compressibility equation is **R.L.B[9]**:

$$\frac{v_t}{4\beta_e}\dot{P}_L = -A\dot{x}_p - C_{tp}P_L + Q_L \tag{2}$$

Where V_t represents the volume of the total actuator, β_e is the effective bulk modulus of oil, x_p is the actuator piston position, A is theactuatorram area, C_{tp} is the coefficient of total leakage, and Q_L is Load flow.

Load flow (Q_L)can be described by the following equation **Danial [7];**

$$Q_L = C_d w x_v \sqrt{\frac{P_s - \mathrm{sgn}(x_v)P_L}{\rho}} \tag{3}$$

Where C_d represents the coefficient of discharge, w is the area gradient of spool valve, P_s is the pressure of the supply, ρ is the density of the fluid and defining the load pressure (P_L) as $P_L = P_1 - P_2$ and the load flow (Q_L) as $Q_L = (Q_1 + Q_2)/2$,

The piston force equation is given by **R.L.B** [9]:

$$P_L A = m\ddot{x_p} + K\dot{x_p} + F_f \tag{4}$$

Where K represents the spring constant, F_f is the force of the friction and m is the piston mass and load. From Eq(1-4) if the state variables selected as:
x=[$x_1\, x_2\, x_3\, x_4\ x_5$]=[$x_p\, \dot{x}_p P_L\, x_v\, \dot{x}_v$] the overall system can be written in state space form

$$\dot{x}_1 = x_2 \tag{5}$$
$$\dot{x}_2 = \frac{1}{m}\left(-Kx_2 + Ax_3 - F_f\right) \tag{6}$$
$$\dot{x}_3 = -\alpha x_2 - \beta x_3 + \gamma x_4\sqrt{P_s - sgn(x_4)x_3} \tag{7}$$
$$\dot{x}_4 = x_5 \tag{8}$$
$$\dot{x}_5 = -w_n^2 x_4 - 2\zeta_n w_n x_5 + w_n^2 K_v u \tag{9}$$

Where
$\alpha = 4A\beta_e/V_t$
$\beta = 4C_{tp}\beta_e/V_t$
$\gamma = 4C_d\beta_e w/V_t\sqrt{\rho}$

Abrasion in the hydraulic cylinder has been taken into consideration as an outer disturbance

3. FRICTION MODEL

Friction is described as the resistance to motion when two surfaces slide against each other **Efe [10]**. Abrasion appears in such mechanical systems as hydraulic cylinders, pneumatic cylinders, bearings, transmissions, valves, wheels, and brakes. It can lead to undesirable effects such as limit cycle oscillation, tracking mistakes and unfavorable stick-slip move **Olsson et al. [11]**.

Friction has usually been demonstrated as intermittent charting between the velocity and the force of friction. The equations below present the LuGre friction model:

$$F_f = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 \dot{x}_p \qquad (10)$$

$$\dot{z} = \dot{x} - \frac{|\dot{x}|}{g(\dot{x})} z \qquad (11)$$

where z is the state of internal friction, $\dot{x_p}$is the relative velocity between two surfaces, σ_0, σ_1, and σ_2 are the stiffness of the bristle between two contact surfaces, the bristles damping coefficient, and the viscous friction coefficient, respectively. The Stribeck effect characteristic can be parameterized as a nonlinear function$g(\dot{x})$, that can be chosen to designate various friction influences **[12].**

$$g(\dot{x}) = \frac{1}{\sigma_0}\left(F_c + (F_s - F_c)e^{-(\dot{x_p}/v_s)^2}\right) \qquad (12)$$

Where F_s is the friction of viscous, F_c is the Coulomb friction and v_s is the stribeck velocity. **Fig.2** illustrates the features of the abrasion-velocity of this sample. It shows the features of dynamic and static friction. The features of friction are produced through two cycle fluctuation. The fluctuationis created in narrow hysteretic influences around the zero relative velocity in the graph **Jerzy et al. [13]**.

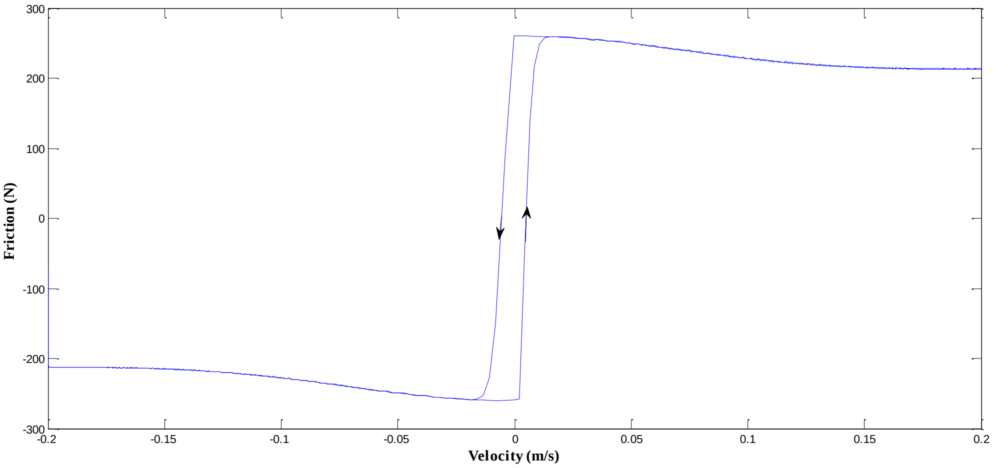

Figure 2. Description of friction-velocity

4. FUZZY LOGIC POSITION CONTROLLER OF THE ELECTRO-HYDRAULIC SERVO-ACTUATOR:

Fig.4 shows the SIMULINK block diagram of the EHSS with the abrasion made from Eq(1-12) by the utilization of FLC methodology. **Fig. 5** represents the respective block diagram of the position control system. The regulator transmits the control signals which are considered by the control algorithm to the servo amplifier all that by the use of reference signal as well as a feedback signal which come from the location sensor with the hydraulic cylinder.

The constituents of an FLC are the Fuzzfier, the Inference Engine, and the Fuzzy Knowledge base as well as the Defuzzifier. Based on Fig. 6, the Fuzzifier changes the crisp of input to a linguistic variable through the use of the MFs in the Fuzzy Knowledge-base. On the other hand, by the utilization of *If-Then* kind fuzzy rules, the inference engine changes the fuzzy input to a fuzzy output. Defuzzifier, in turn, changes the fuzzy output of the inference engine into a crisp one **Passino and Yurkovich [14].**

In this study, FLC is made up of two variables of input and one variable of output. The variables of input are the errors and the alteration in error while the control voltage is the output variable. The input of error, the change in error and the variables of output have five functions of membership which are described in the universe of discourse as clarified in **Fig.7**. The FLC is made up with 25 rules as shown in **Table 2**. Three scaling aspects GE, GCE, and GU are presented to create regularized input as well as output signals of the fuzzy logic regulator as shown in **Fig.5**. Scaling aspects of inputs and output have been utilized to regulate the control features of the fuzzy controllers for the control system dynamic features

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The fuzzy Graphical User Interface (GUI) in MATLAB/SIMULINK package has been used for the implementation of the FLC. The parameters of the fuzzy controller (input and output memberships) have been loaded by M.file program using method of structure **[15]**. **Fig.3** shows the parameters of the MF, Where a, b and c represent the triangular MF parameters, *i* is the input and j is the number of MF. The initial parameters illustrate in Table 1 (a, b and c).

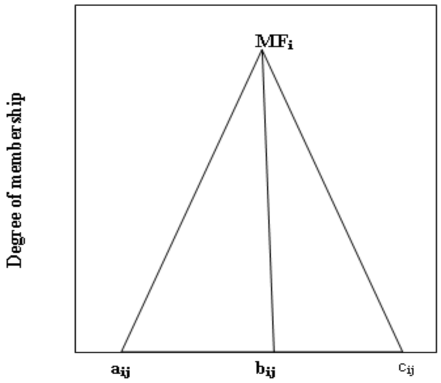

Figure 3. Membership function

Table 1-a: parameters of error membership (Input 1)

a_{11}	b_{11}	c_{11}	a_{12}	b_{12}	c_{12}	a_{13}	b_{13}	c_{13}	a_{14}	b_{14}	c_{14}	a_{15}	b_{15}	c_{15}
-1	-1	-0.5	-1	-0.5	0	-0.5	0	0.5	0	0.5	1	0.5	1	1

Table 1-b: parameters of change of error (Input 2)

a_{21}	b_{21}	c_{21}	a_{22}	b_{22}	c_{22}	a_{23}	b_{23}	c_{23}	a_{24}	b_{24}	c_{24}	a_{25}	b_{25}	c_{25}
-1	-1	-0.5	-1	-0.5	0	-0.5	0	0.5	0	0.5	1	0.5	1	1

Table 1-c: parameters of change of control action (Output)

a_{o1}	b_{o1}	c_{o1}	a_{o2}	b_{o2}	c_{o2}	a_{o3}	b_{o3}	c_{o3}	a_{o4}	b_{o4}	c_{o4}	a_{o5}	b_{o5}	c_{o5}
-1	-1	-0.5	-1	-0.5	0	-0.5	0	0.5	0	0.5	1	0.5	1	1

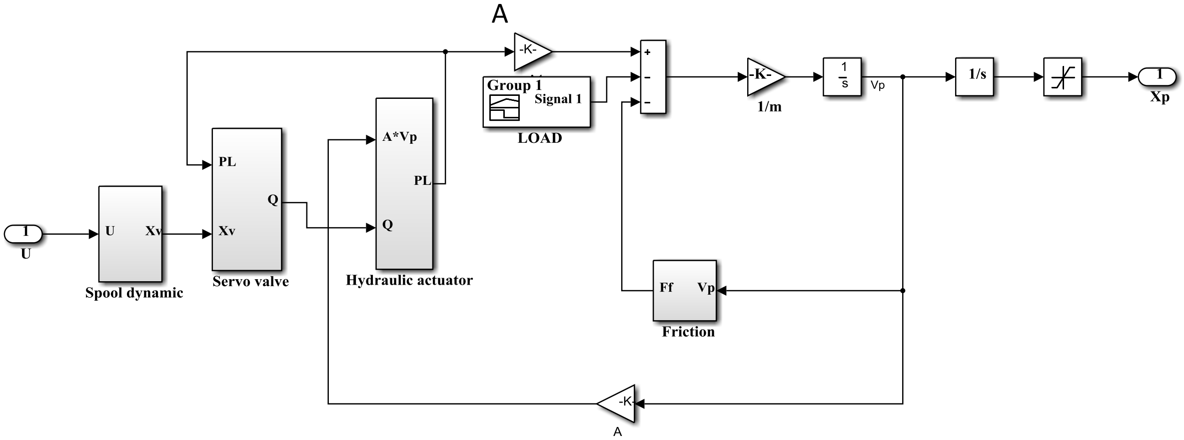

Figure 4. The SIMULINK model of electro-hydraulic system with friction

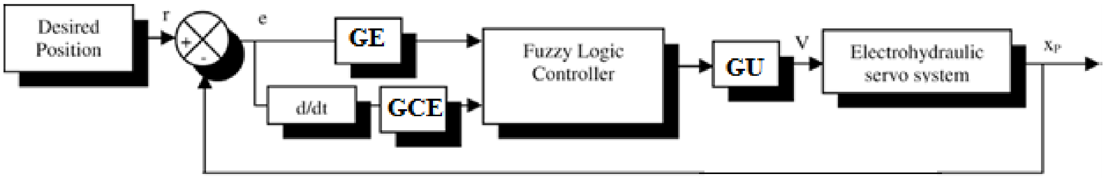

Figure 5. Hydraulic control block diagram

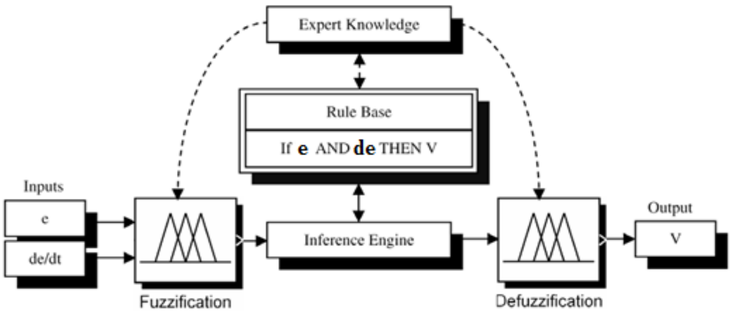

Figure 6. Fuzzy logic controller

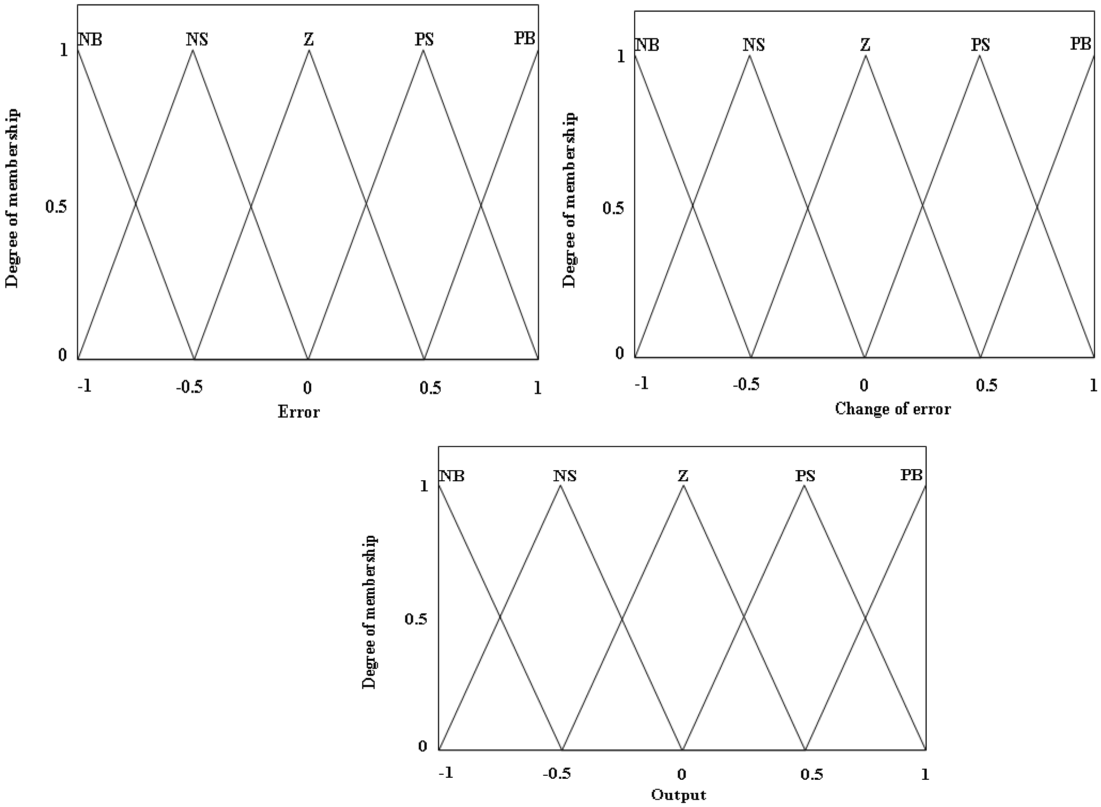

Figure 7. Input and output membership

Table 2: Fuzzy control rule

e \ ce	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

5. PD-LIKE FLC

The structure of the PD-like FLC is [5]:

$$u_o = GE * e + GCE * \frac{de}{dt} \qquad (13)$$

$$u = GU * u_o \qquad (14)$$

Where *GE* and *GCE* are the error scaling factors and error change of error respectively, u_o is the controller action, and *GU* is the output scaling factor.

Three types of fitness function are considered in evolution the FLC parameters:

1- Integral Time Absolute Error.

$$f1 = \int_0^T t|e(t)|dt + max(e) \qquad (15)$$

2- Integral Absolute Error.

$$f2 = \int_0^T |e(t)|dt + max(e) \qquad (16)$$

3- Integral Square Error.

$$f3 = \int_0^T e^2(t)dt + max(e) \qquad (17)$$

The max *e* value adds to the fitness function to obtain optimization parameters with small value of overshoot in response.

6. PARTICLE SWARM OPTIMIZATION (PSO)

The PSO algorithm has been projected by the **Kennedy and Eberhart [16]**. The so-called PSO is a populace based stochastic optimization strategy stimulated by the behavior of groups like birds flocking, in search for food. Particle swarm optimization is simple, easy to realize and has verydeep intelligent background. The possible solutions that are called particles fly arbitrarily through the D-dimension problem space to search the solutions in which the fitness f can be considered as the exact measure of qualities. The motion of particles has been directed by the best-known location of each particle in the search space and the whole group's best-known location. This process keeps continuing until a reasonable solution is found out. The purpose is to find the global best (Gbest) solution among all the current best solutions (Pbest).

The apprising velocity and the position of each particle can be considered by the use of the present velocity and the distance from ($Pbest_i$) to (Gbest) as illustrated by the following formula **Solihin et al.[17] Youssef et al. [18] Karam[19]**:

$$V_i^{(t+1)} = W.V_i^{(t)} + c_1.r_1\left(Pbest_i - X_i^{(t)}\right) + c_2.r_2\left(Gbest - X_i^{(t)}\right) \qquad (18)$$

$$X_i^{(t+1)} = X_i^{(t+1)} + V_i^{(t+1)} \qquad (19)$$

Where c_1 is the factor of self-confidence, c_2 is the factor of swarm confidence, *W* inertia factor, r_i are a random numbers between [0,1] for *i*-thparticle. **Fig.8** shows a flowchart depicting the typical PSO.

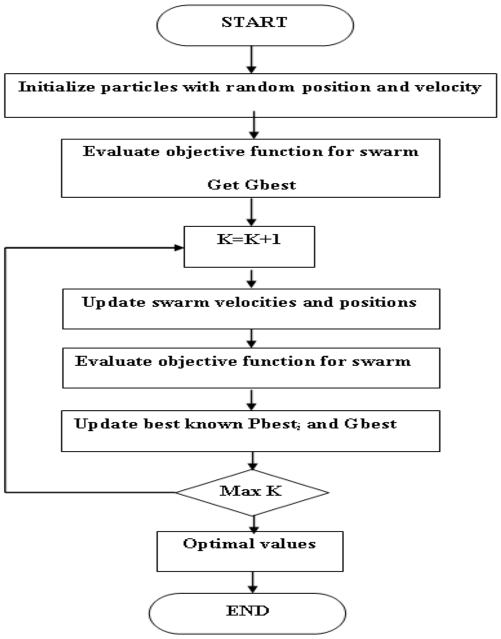

Figure 8. PSO flowchart

7. RESULTS:

The MATLAB/SIMULINK program is used for the implementation of the PSO algorithm to tuning the FLC and modeled the hydraulic system. The parameters of the EHSS are given in **Table 3 Mihajlov and Nikolic [20].** Figure 9 depicts the system step response with no load (free motion) according to minimize the ITAE criteria. This figure gives a good transient and steady state response. **Table 4**(a, b and c) shows the MF parameters of the PD fuzzy controller structure. This table illustrates the change in membership parameters. The effect of the load is dissipating in **Fig.10**. One kN is added to the EHSS at time 0.4sec. The proposed controller algorithm is canceled the effect of the load. This response is better than that achieved by **Miroslav and Nikolić [20]**. The effect of the different fitness criteria on the response of the system is shown in **Fig.11**. Each criterion uses to tune the FLC with same dimensions and number of iterations. The speed up and the value of overshoot is the main different between them. The IAE gives high overshoot and fast response compared with ITAE. **Fig.12** shows the transient and steady state response tests for different step inputs. Good tracking performance is observed in this case. The tracking performance of the design controller of the system is describing in **Fig.13**. This test is used to investigate the controller validity in path-following of hydraulic actuator.

Table 3: EHSS parameters

Name	Symbol	Nominal Value	Unit
Pressure of the Supply	Ps	1.034×10^{7}	Pa
Volume of the Total actuator	V_t	6.535×10^{-5}	m^3
Effective bulk modulus	β_e	10^{9}	Pa
Area of the Actuator ram	A	3.2673×10^{-4}	m^2
Coefficient of the Total leakage	C_{tp}	2×10^{-12}	$m^3/(s\ Pa)$
Coefficient of the Discharge	C_d	0.6	
Spool valve area gradient	w	0.022	m
Densityof the Fluid mass	ρ	840	kg/m^3
Actuator and load mass	m	24	kg
Spring constant	k	16010	N/m
Static friction	F_s	260	N
Coulomb friction	F_c	200	N
Viscous friction	F_{visc}	60	N/(m/s)
Stiffness coefficient	σ_0	12×10^{5}	m/s
Damping coefficient	σ_{1e}	300	N s/m
Stribeck velocity	v_s	0.1	m/s

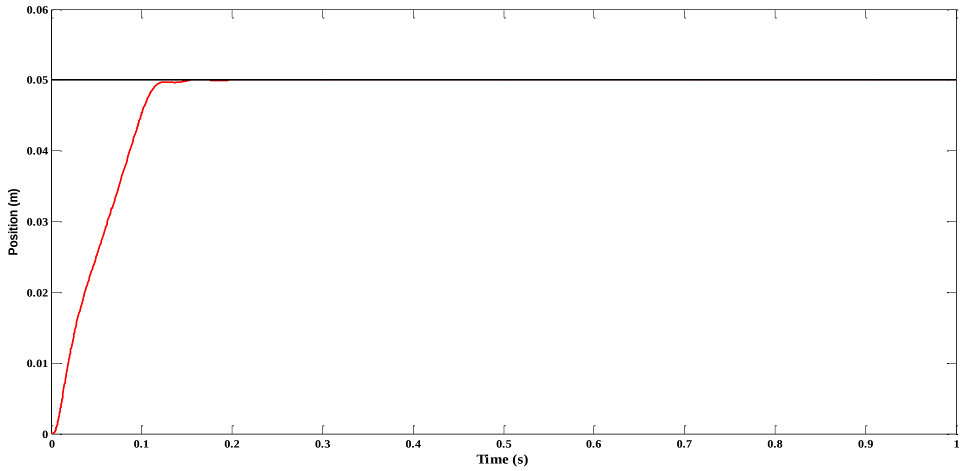

Figure 9. Step response with no load for ITAE criteria

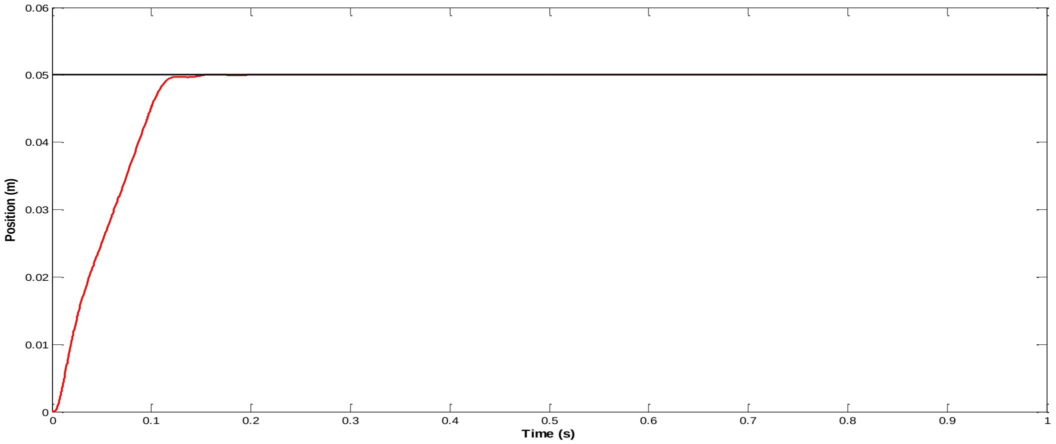

Figure 10. Step response with load 1kN at time 0.4sec for ITAE criteria

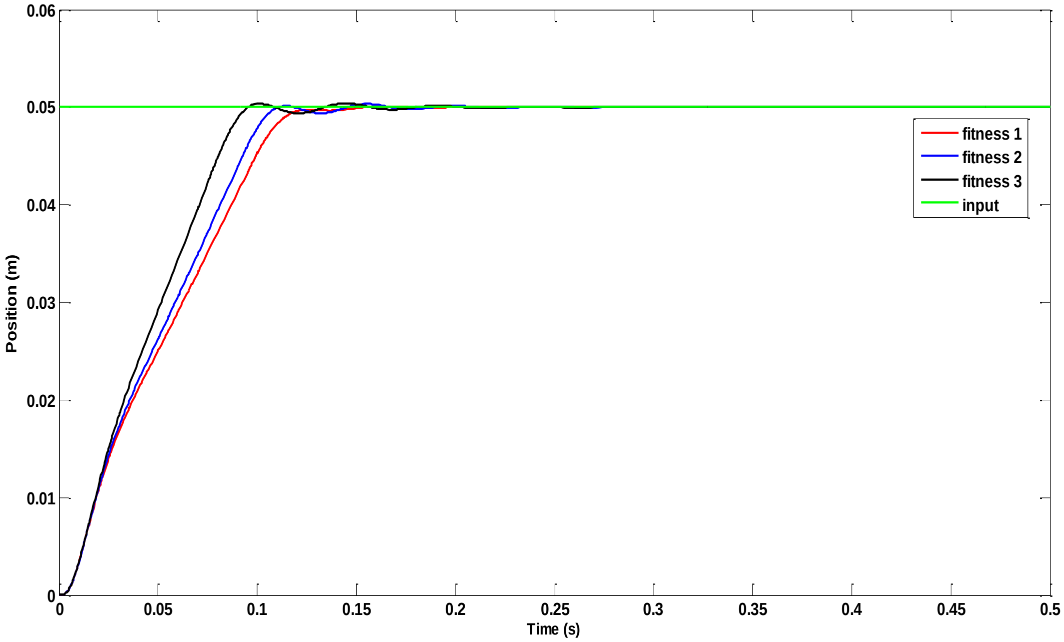

Figure 11. Step response for different criteria

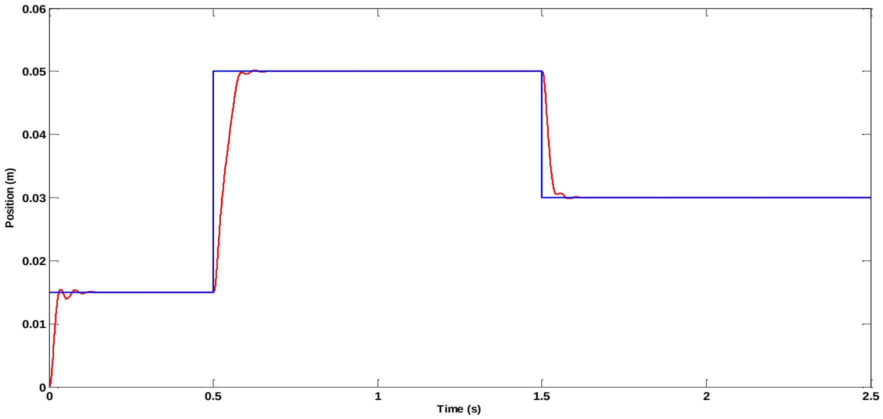

Figure 12. Step response for random input

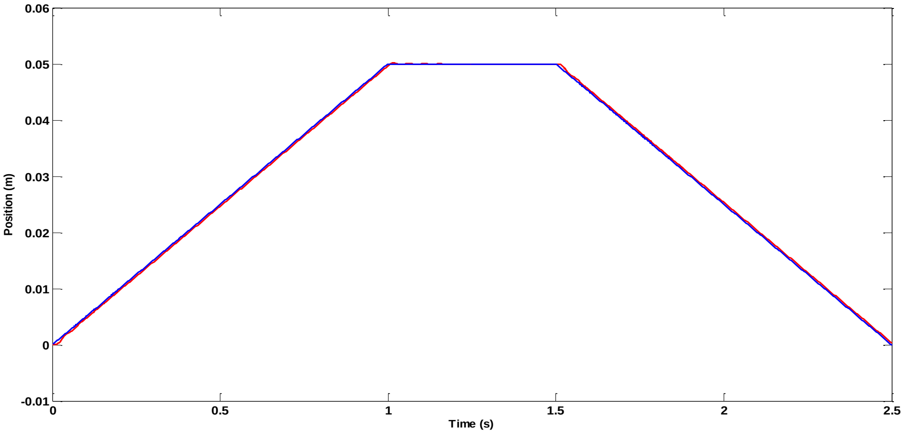

Figure 13. Response of the system with ramp input

Table 4-a: parameters of error membership (Input 1)

a_{11}	b_{11}	c_{11}	a_{12}	b_{12}	c_{12}	a_{13}	b_{13}	c_{13}	a_{14}	b_{14}	c_{14}	a_{15}	b_{15}	c_{15}
-1	-1	-0.05	-0.1	-0.05	0	-0.05	0	0.05	0	0.05	0.1	0.05	1	1

Table 4-b: parameters of error change membership (Input 2)

a_{21}	b_{21}	c_{21}	a_{22}	b_{22}	c_{22}	a_{23}	b_{23}	c_{23}	a_{24}	b_{24}	c_{24}	a_{25}	b_{25}	c_{25}
-1	-1	-0.05	-0.1	-0.05	0	-0.05	0	0.05	0	0.05	0.1	0.05	1	1

Table 4-c: parameters of control action membership (Output)

a_{o1}	b_{o1}	c_{o1}	a_{o2}	b_{o2}	c_{o2}	a_{o3}	b_{o3}	c_{o3}	a_{o4}	b_{o4}	c_{o4}	a_{o5}	b_{o5}	c_{o5}
-1	-1	-0.08	-0.17	-0.08	0	-0.08	0	0.08	0	0.08	0.17	0.08	1	1

8. CONCLUSIONS:

In this paper, MATLAB/SIMULINK software package is used for the implementation of the EHSS and FLC. The PD which is like FLC had been made to regulate the location of the electro-hydraulic actuator model. The FLC optimal parameters of the input, output and scaling factors (48 parameters) are tuning based on the PSO algorithm. The main fitness function ITAE criterion is used to obtain the best values of the FLC. Furthermore, different criteria are used in the same system for comparison. The friction and external force effects are introduced in electro-hydraulic model. The performance of the EHSS that is under the controller has been examined. The results of the imitation present the efficiency of the controller proposed.

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NOMENCLATURE

A	actuator ram area
c_1	factor of self-confidence
c_2	factor of swarm confidence
C_d	coefficient of discharge
C_{tp}	coefficient of total leakage
F_f	force of the friction
F_s	friction of viscous
F_c	Coulomb friction
K	spring constant
k_v	gain of the servo valve
m	piston mass and load
P_s	pressure of the supply
P_L	load pressure
r_i	random numbers
Q_L	Load flow.
V_t	volume of the total actuator
v_s	stribeck velocity
u	input volltage
W	inertia factor
w	area gradient of spool valve
x_p	actuator piston position
$\dot{x}_p$	relative velocity between two surfaces,
z	state of internal friction

Greek Symbols

β_e	effective bulk modulus of oil
ζ_v	damping ratio
σ_0	stiffness of the bristle between two contact surfaces
σ_1	bristles damping coefficient
σ_2	viscous friction coefficient
ρ	density of the fluid
ω_v	equivalent natural frequency