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# CONVENTIONAL AND EVOLUTIONARY CONTROL SCHEMES FOR SPRING-ROLL DIELECTRIC ELASTOMER ACTUATOR

***Mohamed I. El-Adawy***

*Communication, Electronics and Computer Department,*
*Faculty of Engineering, Helwan University,*
*Cairo, Egypt.*

***Ahmed M. El-Garhy***

*Electronics and Communication Dept.,*
*Faculty of Engineering, Helwan University,*
*Cairo, Egypt.*
*E mail: agarhy2003@yahoo.co.in*

***Besada A. Anees***

*Industrial Training Council,*
*Cairo, Egypt.*
*E mail: bessada_adib@yahoo.com*

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*To control the actuation of the spring-roll dielectric elastomer actuator, the required actuation and dimensionless axial force (load) should be prescribed. Required actuation can be considered as a set point of the control system. In this paper different conventional and evolutionary controllers have been proposed, PID, Fuzzy, PID-Fuzzy average, particle swarm optimizing algorithm based PID. The performance of all these controllers have been addressed in terms of steady state error, maximum overshoot, and time consumed for the sake of qualitative comparison. To control the actuation of the spring-roll dielectric elastomer actuator, the charges pumped by the voltage supply should be controlled. A unity feed back control system is used.*

*The response of each control system is derived and the choice of the more suitable controller is an application dependent, where some applications need zero steady state error while others need fast response. Spring-roll dielectric elastomer voltage supply and control system are based upon optimal design parameters derived in [1, 2]. The results of the conducted simulation experiments proved that all developed control systems are robust and help the usage of the spring-roll dielectric elastomer as a structural unit of an active artificial muscle.*

***KEY WORDS:*** *Spring-roll dielectric elastomer actuator, PID controller, PSO based PID controller, Fuzzy controller, PID-fuzzy average controller.*

## 1. INTRODUCTION

Dielectric elastomer actuators have been intensely studied in the recent decade. When the actuator is subjected to an applied voltage and an applied axial force, the axial elongation couples the electrical and mechanical actions. The construction of a spring-roll dielectric elastomer actuator was indicated in [3-6].

Providing dielectric elastomer actuators with a level of pre-stretch can improve properties such as breakdown strength, actuation strain and efficiency. The parameters of design include the prestretches of the elastomer and the stiffness of the spring.

Equations of state of the dielectric elastomer actuator were derived from its Helmholtz free energy. Equations of state namely are;

$$\frac{p}{\mu L_2 L_3} = \left(\lambda_1 - \lambda_1^{-3}\left(\lambda_2^p\right)^{-2}\right) - \frac{1}{\lambda_1^3\left(\lambda_2^p\right)^2}\left(\frac{q}{\sqrt{\mu\varepsilon}L_1 L_2}\right)^2 + \alpha\left(\lambda_1 - \lambda_1^p\right) \tag{1}$$

$$\frac{\phi}{L_3}\sqrt{\frac{\varepsilon}{\mu}} = \frac{1}{\left(\lambda_1\lambda_2^p\right)^2}\left(\frac{q}{\sqrt{\mu\varepsilon}L_1 L_2}\right) \tag{2}$$

where

$p$ : is the axial force with which the actuator is loaded in Newtons.

$\mu$ : is the shear modulus of the dielectric elastomer material in Pascals.

$L_1,\ L_2,\ and\ L_3$: are the actuator membrane length, width, and thickness in meters.

$\lambda_1$ : is the elongation or actuation the actuator has to actuate.

$\lambda_1^p,\ \lambda_2^p\ and\ \lambda_3^p$: are pre-stretches in actuator membrane length, width, and thickness.

$\alpha$ : is the spring stiffness.

$q$: is the charge accumulated on one of the electrodes of the dielectric elastomer actuator in Coulombs.

$\varepsilon$ : is the dielectric of the elastomer material in Farads/meter.

$\phi$: is the voltage applied to the electrodes of the dielectric elastomer actuator in Voltages.

$\frac{p}{\mu L_2 L_3}$ : is the dimensionless axial force $P$.

$\frac{q}{\sqrt{\mu\varepsilon}L_1 L_2}$ : is the dimensionless charge $Q$.

$\frac{\phi}{L_3}\sqrt{\frac{\varepsilon}{\mu}}$ : is the dimensionless applied voltage $\Phi$.

Parameters of design and actuator dimensions are prescribed once the actuator is constructed therefore they must be well selected to be optimal. Spring-roll dielectric elastomer optimal design parameters are $\lambda_1^p = 5,\ \lambda_2^p = 5,\ \alpha = 10$.

To control the actuation of the spring-roll dielectric elastomer actuator, the required actuation and dimensionless axial force (load) have to be prescribed. Required actuation is used as a set point of the control system. In this paper different kinds of controllers, PID controller, Fuzzy controller, PID-Fuzzy average controller, particle swarm optimizing algorithm based PID controller are used. Rise time, settling time, percentage overshoot, and steady state error of each of these controllers are compared to evaluate its performance. Robust control helps the usage of the spring-roll dielectric elastomer as a structural unit of an active artificial muscle.

The rest of the paper is organized as follows: Section 2 describes the specifications of voltage supply that pumps charges to the spring-roll dielectric elastomer actuator. Section 3 explains a general view of spring-roll dielectric elastomer actuator control system. Section 4 explains traditional (conventional) and evolutionary control systems that can be used to control spring-roll dielectric actuators. Section 5 demonstrates simulation of these control systems and response of each system and. The derived conclusion is given in section 6.

## 2. SPRING-ROLL DIELECTRIC ELASTOMER ACTUATOR CONTROLLED VOLTAGE SUPPLY

A DC voltage supply output $\Phi$ is applied to the spring-roll dielectric elastomer actuator. It pumps charges $Q$ to complaint electrodes of the actuator. The voltage supply can be mathematically modeled by eq. 2 where dimensionless $\Phi$ and dimensionless $Q$ have a linear relationship whose slope depends upon the required actuation $\lambda_1$. Figure 1 illustrates that dimensionless $Q$ increases proportionally to dimensionless $\Phi$. $Q$ can be controlled by controlling $\Phi$.

The efficiency of the spring-roll dielectric elastomer is high because it uses static charges and does not consume power due to dynamic currents.

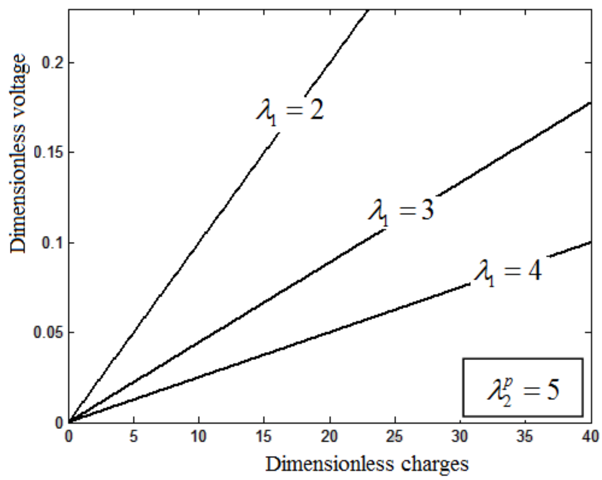


Fig. 1: Dimensionless Q versus Φ.

## 3. SPRING-ROLL DIELECTRIC ELASTOMER ACTUATOR CONTROL SYSTEM

A unity feedback control system is used to control the actuation of the spring-roll dielectric elastomer actuator. When $\lambda_1$ is larger or lower than $\lambda_{1req}$ ($\lambda_{1error} \neq 0$) the controller controls the dimensionless voltage of the voltage supply which in turn controls the dimensionless charge that out from the voltage supply and accumulated on the compliant electrodes of the actuator. The controlled charge controls the actuation $\lambda_1$ and get it equal $\lambda_{1req}$.

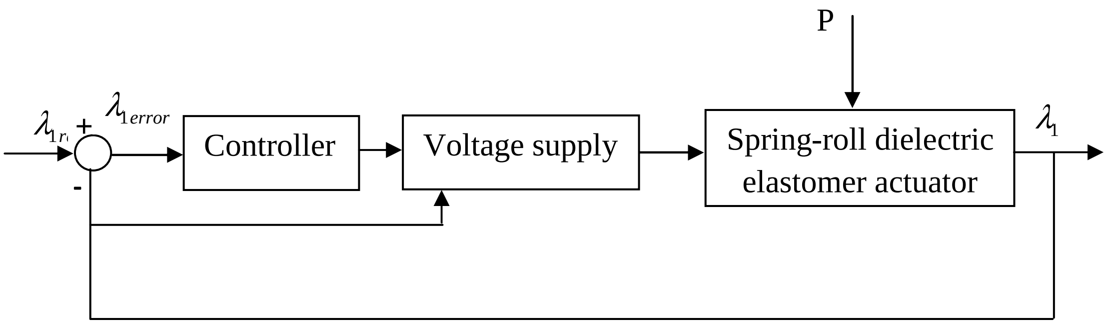


Fig. 2: Spring-roll dielectric elastomer actuator control system.

The dimensionless axial force P and the required actuation $\lambda_{1req}$ are a coupled pair. When P is changed, $\lambda_{1req}$ has to be changed. Experimentally, when optimal design parameters ($\lambda_1^p = 5,\ \lambda_2^p = 5,\ \alpha = 10$) are used, P ranges from 0 to -36 and $\lambda_{1req}$ ranges from $\lambda_1^p/4$ (*the compressive limit of the spring*, a failure mode) to the value "5" (*the tensile rupture of the elastomer*, another failure mode).

To start simulating the control system, we have to simulate the voltage supply and the spring-roll dielectric elastomer actuator. Eq. 1 (the mathematical model of the voltage supply) and eq. 2, the mathematical model of the spring-roll dielectric elastomer actuator, are simulated using Matlab Simulink, as shown in Figures 3 and 4.

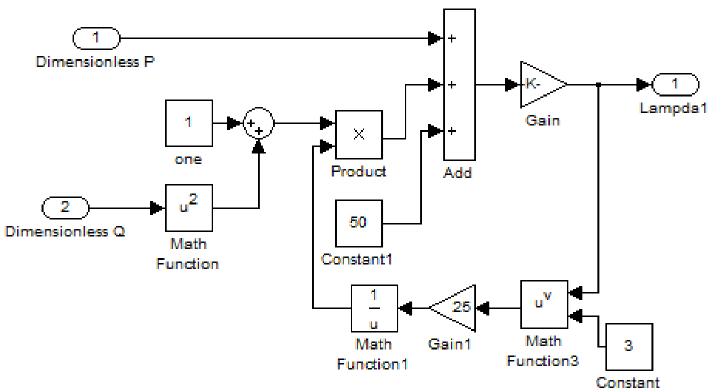


Fig. 3: Simulink model of spring-roll dielectric elastomer actuator

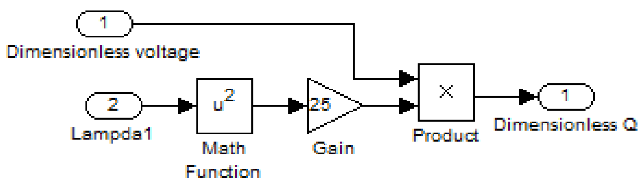


Fig. 4: Simulink model of voltage supply

# 4. SPRING-ROLL DIELECTRIC ELASTOMER ACTUATOR CONVENTIONAL AND EVOLUTIONARY CONTROL SYSTEMS

## 4.1 PID controller

Even in a decade where advanced control algorithms mostly based on some kind of optimization procedures have achieved a high degree of maturity, Proportional Integral Derivative (PID) controllers are still widely used in industrial applications even though many new control techniques have been proposed [7]. The reason is that it has a simple structure which is easy to be understood by engineers, and practical conditions, it performs more reliable compared to more advanced and complex controllers [8]. PID controllers improve the transient response of a system by reducing the overshoot, and by shortening the settling time of a system [9]. PID controller is the cornerstone for many advanced control algorithms and strategies. For these reasons, it is the first choice for new controller design.

### 4.1.1 PID Controller tuning:

One of PID controller tuning methods is the Ziegler-Nichols [10]. Ziegler-Nichols method basically boils down to these two steps:

*Step 1:* Set $k_i$ and $k_d$ to zero. Excite the system with a step command. Slowly increase $k_p$ until it reaches the ultimate gain, ku, at which the output of the loop starts to oscillate. At this point, record the value of $k_p$ and set $k_o$ to it. Record the oscillation frequency $f_o$.

*Step 2:* Set the final PID gains using the following eq.

$$k_p = 0.6\ k_o,$$
$$k_i = 2\ f_o\ k_p \tag{3}$$
$$k_d = \frac{k_p}{8\ f_o}$$

The results using PID controller are illustrated in section 5.

## 4.2 Fuzzy controller

Benefits of Artificial intelligence (AI) based control systems compared to other classical control methods, has encouraged many interested researches to study and design such systems. Reviewing and comparing conventional and intelligent control systems, many articles showed the importance of AI in new controllers [11]. Artificial intelligence based control methods especially in the case of non-linear systems or when system has many complications, are very efficient, because in these cases the system cannot be addressed simply by equations and mathematical descriptions.

In fuzzy control systems, human knowledge in the form of fuzzy if-then rules is the foundation for decision making in fuzzy inference system (FIS). In a fuzzy control system, system parameters are crisp numbers, they must change into fuzzy sets by fuzzifier to be able to react as the fuzzy inference engine inputs. Fuzzy inference engine interprets fuzzy input sets and assesses them with fuzzy if-then rules, finally the results will expressed by fuzzy output sets. Since, the equipments react by crisp inputs, fuzzy output sets have to change into crisp numbers by defuzzifier. The various parts of a fuzzy control system are shown in figure 5.

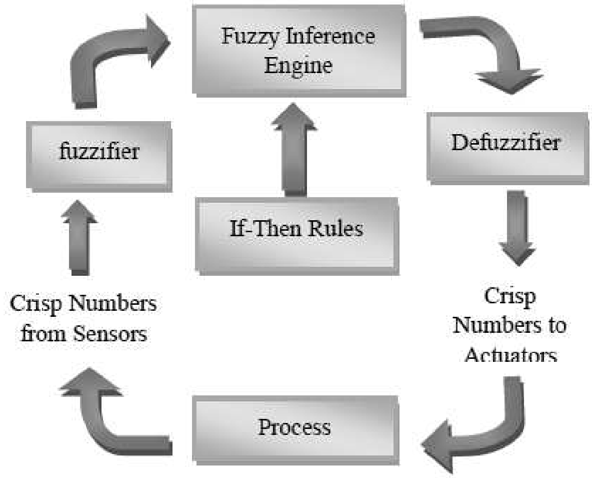


Fig. 5: Various parts of a fuzzy control system.

The difference between $\lambda_{1req}$ and $\lambda_1$ is the error $\lambda_{1error}$ which ranges from -4.7 to +4.7 in the spring-roll dielectric elastomer control system. This range in the proposed fuzzy control system is occupied by five triangular membership functions; neg2, neg1, zero, pos1, and pos2. Figure 6 shows these membership functions. The above mentioned range is derived from the curves of equations of state and failure modes.

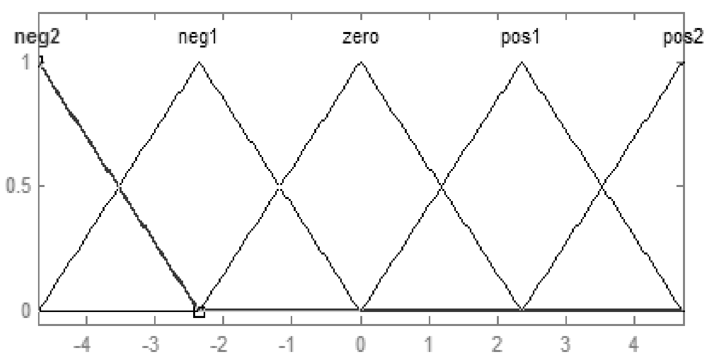


Fig. 6: Membership functions of Fuzzy controller input

The output of the proposed fuzzy controller, the dimensionless applied voltage, ranges from 0 to 0.14. This range is occupied by five triangular membership functions; low2, low1, med, high1, and high2. Figure 7 shows these membership functions. The above mentioned range is also derived from the curves of equations of state and failure modes.

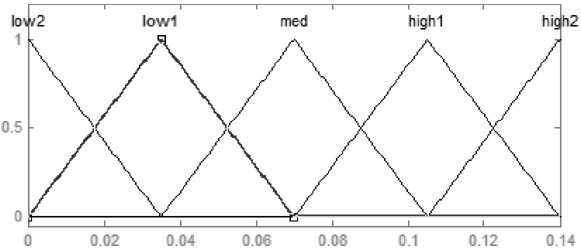

Fig. 7: Membership functions of Fuzzy controller output

### 4.2.1 Fuzzy inference and if-then rules

The proposed fuzzy controller is single input ($\lambda_{1\,error}$ or error) single output (dimensionless voltage). If-then rules of the proposed fuzzy control system are;
If (error is neg2) then (phi is low2)
If (error is neg1) then (phi is low1)
If (error is zero) then (phi is med)
If (error is pos1) then (phi is high1)
If (error is pos2) then (phi is high2)
The results of fuzzy controller are illustrated in section 6.

A unity feed back control system is not suitable for fuzzy logic controller because of the problem of input data dependency violation due to action sub-systems, therefore a unit delay with sample time $10^{-6}$ sec is included as a feedback unit. The results of this method are illustrated in section 5.

## 4.3 PID-Fuzzy average controller

Combination of conventional control methods and fuzzy control is an attractive research area where we benefit the advantages of both PID controller and fuzzy controller. The steady state error using PID controller is zero but the steady state error using fuzzy controller is not zero and the settling time using fuzzy controller is too short but that of the PID controller is not short compared to fuzzy controller therefore both PID and fuzzy controller are used together and the average of their output are used. The results of this method are also illustrated in section 6.

## 4.4 PSO-Based PID controller

### 4.4.1 Particle Swarm Algorithm

The PSO concept consists of, at each time step, changing the velocity of each particle toward its pbest and gbest locations. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and gbest locations.

For example, the jth particle is represented as $x_j = (x_{j,1}, x_{j,2}, ........x_{j,g})$ in the g-dimensional space. The best previous position of the jth particle is recorded and represented as $pbest_j = \left(pbest_{j,1}, pbest_{j,2}, ........pbest_{j,g}\right)$. The index of best particle among all of the particles in the group is represented by the $gbest_g$. The rate of the position change (velocity) for particle j is represented as $v_j = (v_{j,1}, v_{j,2}, \ldots\ldots v_{j,g})$. The modified velocity and position of each particle can be calculated using the current velocity and the distance from $pbest_{j,g}$ to $gbest_g$ as shown in the following formulas:

$$v_{j,g}^{t+1} = w.v_{j,g}^{t} + c_1 * rand() * (pbest_{j,g} - x_{j,g}^{t}) + c_2 * rand() * (gbest_g - x_{j,g}^{t}) \qquad (4)$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)} \qquad (5)$$

$$j = 1, 2, \ldots\ldots n$$

$$g = 1, 2, \ldots\ldots m$$

where;

| | |
|---|---|
| $n$ | number of particles in a group |
| $m$ | number of members in a particle |
| $t$ | pointer of iterations (generations) |
| $v_{j,g}^{t}$ | velocity of particle $j$ at iteration $t$, $v_g^{\min} \le v_{j,g}^{t} \le v_g^{\max}$ |
| $w$ | inertia weight factor |
| $c_1, c_2$ | acceleration constants |
| $rand(), rand()$ | random numbers between 0 and 1 |
| $x_{j,g}^{t}$ | current position of particle $j$ at iteration $t$ |
| $pbest_j$ | pbest of particle $j$ |
| $gbest$ | gbest of the group |

In the above procedures, the parameter $V^{\max}$ determined the resolution, or fitness, with which regions be searched between the present position and the target position. If $V^{\max}$ is too high, particles might fly past good solutions. If $V^{\max}$ is too small, particles may not explore sufficiently beyond local solutions. In many experiences with PSO, was often set at 10–20% of the dynamic range of the variable on each dimension.

The constants $c_1$ and $c_2$ represent the weighting of the stochastic acceleration terms that pull each particle toward $pbest$ and $gbest$ positions. Low values allow particles to roam far from the target regions before being tugged back. On the other hand, high values result in abrupt movement toward, or past, target regions. Hence, the acceleration constants $c_1$ and $c_2$ were often set to be 2.0 according to past experiences.

Suitable selection of inertia weight $w$ provides a balance between global and local explorations. $w$ often decreases linearly from about 0.9 to 0.4 during a run.

### 4.4.2 Performance Estimation of PID Controller

The following performance criterion in time domain is used for evaluating the PID controller where overshoot $M_p$, rise time $t_r$, settling time $t_s$, and steady-state error $E_{ss}$ are included.

$$Min\ W(k) = (1-e^{-\beta}).(M_p + E_{ss}) + e^{-\beta}.(t_s - t_r) \tag{6}$$

where $k$ is $[k_p, k_i, k_d]$, and $\beta$ is the weighting factor.

The evaluation function $f$ is a reciprocal of the performance criterion $W(K)$. It implies the smaller $W(K)$ the value of individual $k$, the higher its evaluation value

$$f = \frac{1}{W(K)} \tag{7}$$

The performance criterion $W(k)$ can satisfy the designer requirements using the weighting factor $\beta$ value. We can set $\beta$ to be larger than 0.7 to reduce the overshoot and steady-state error. On the other hand, we can set $\beta$ to be smaller than 0.7 to reduce the rise time and settling time. In this paper, $\beta$ is set in the range of 0.8 to 1.5. A set of good control parameters $k_p$, $k_i$, and $k_d$ can yield a good step response.

### 4.4.3 Spring-roll dielectric elastomer actuator transfer function

Spring-roll dielectric elastomer actuator electrically is equivalent to a capacitance whose transfer function is $G(s) = \frac{1}{sC}$, where $C$ is the capacitance of the spring-roll dielectric elastomer actuator. Voltage supply transfer function can be derived from eq. 2. If optimal design parameters are used and if we denote $\frac{\phi}{L_3}\sqrt{\frac{\varepsilon}{\mu}}$ by $\Phi$, and $\frac{q}{\sqrt{\mu\varepsilon}L_1L_2}$ by $Q$ then eq. 2 will be;

$\Phi = \frac{Q}{25\lambda_{1req}^2}$, where $\lambda_{1req}$ is a constant value (the set point of the control system).

$$\Phi(t) = \frac{Q(t)}{25\lambda_{1req}^2} = \frac{\int i(t)\,dt}{25\lambda_{1req}^2} \tag{8}$$

$$\Phi(s) = \frac{I(s)}{25\lambda_{1req}^2\, s} \tag{9}$$

$$G(s) = \frac{I(s)}{\Phi(s)} = 25\lambda_{1req}^2\, s \tag{10}$$

### 4.4.4 Proposed PSO-PID Controller [12]

This paper presents a PSO-PID controller for searching the optimal or near optimal controller parameters $k_p, k_i,$ *and* $k_d$ with the PSO algorithm. Each individual $K$ contains three members $k_p, k_i,$ *and* $k_d$. The dimension of the matrix representing the initial population is $n \times 3$.

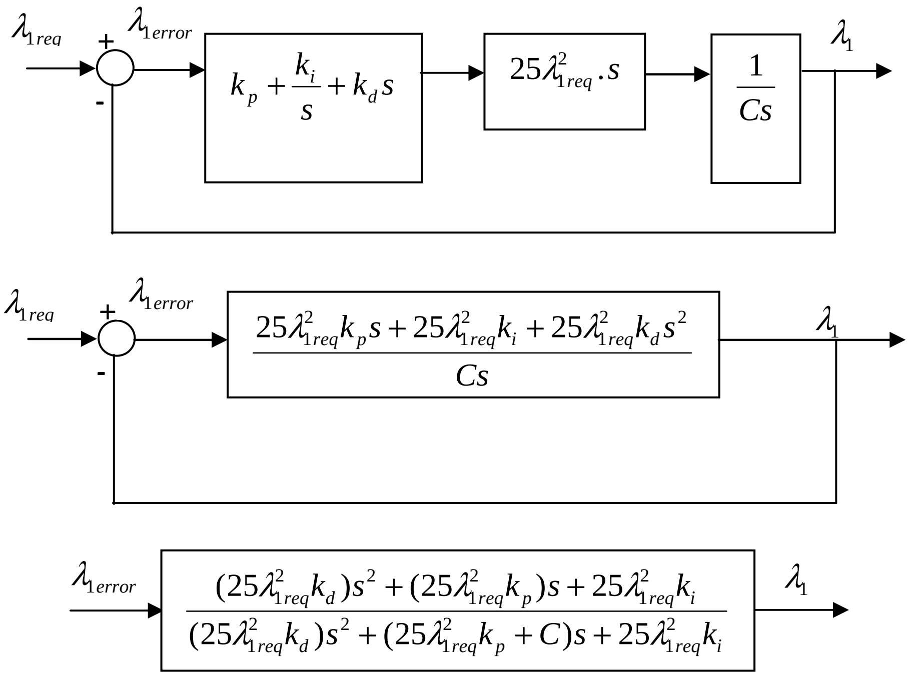


Fig. 8: The closed loop transfer function of the BSO-based PID control system

The searching procedures of the proposed PSO-PID controller were shown as below.

Step 1) Initialize randomly the individuals of the population including searching points, velocities, pbest, and gbest.

Step 2) For each initial individual $K$ of the population, employ the *Routh-Hurwitz* criterion to test the closed-loop system stability and calculate the values of the four performance criteria in the time domain, namely $M_P,\ E_{SS},\ t_r,\ and\ t_s$ .

Step 3) Calculate the evaluation value of each individual in the population using the evaluation function $f$ given by equation (7).

Step 4) Compare each individual's evaluation value with its pbest. The best evaluation value among the pbest is denoted as gbest.

Step 5) Modify the member velocity $v$ of each individual $K$ according to the following eq.

$$v_{j,g}^{t+1} = w.v_{j,g}^{t} + c_1 * rand() * (pbest_{j,g} - x_{j,g}^{t}) + c_2 * rand() * (gbest_g - x_{j,g}^{t})$$
$$j = 1,\ 2,........n$$
$$g = 1,\ 2,........m \qquad (11)$$

where the value of $w$ is set by (18). When g is 1, $v_{j,\,1}$ represents the change in velocity of $k_p$ controller parameter. When g is 2, $v_{j,\,2}$ represents the change in velocity of $k_i$ controller parameter.

Step 6) If $v_{j,\,g}^{t+1} > v_g^{\max}$ , then $v_{j,\,g}^{t+1} = v_g^{\max}$ . If $v_{j,\,g}^{t+1} < v_g^{\min}$ , then $v_{j,\,g}^{t+1} = v_g^{\min}$ .

Step 7) Modify the member position of each individual $K$ according to the following eq.

$$K_{j,\,g}^{(t+1)} = K_{j,\,g}^{(t)} + v_{j,\,g}^{(t+1)}, \qquad (12)$$
$$K_g^{\min} \le K_{j,\,g}^{(t+1)} \le K_g^{\max}$$

where $K_g^{\min}$ and $K_g^{\max}$ represent the lower and upper bounds, respectively, of member g of the individual $K$. For example, when g is 1, the lower and upper bounds of the $k_p$ controller parameter are $k_p^{\min}$ and $k_p^{\max}$, respectively.

Step 8) If the number of iterations reaches the maximum, then go to Step 9. Otherwise, go to Step 2.

Step 9) The individual that generates the latest gbest is an optimal controller parameter.

## 5. SIMULATION AND RESULTS

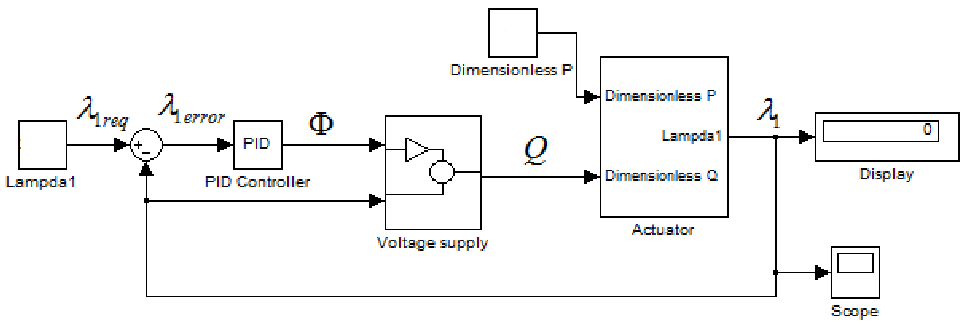


Fig. 9: Spring-roll dielectric elastomer actuator control system using a PID controller

Ziegler-Nichols PID controller tuning

At $k_p$ =4, $k_i$ =0, $k_d$ =0, $P = -18$, and $\lambda_{1req}$ =2.944

$$k_o = 4$$

$$f_0 = 1/0.01 = 100$$

$$k_p = 0.6\,k_o = 0.6 \times 4 = 2.4$$

$$k_i = 2\ f_o\,k_p = 2 \times 100 \times 2.4 = 480$$

$$k_d = \frac{k_p}{8\ f_o} = \frac{2.4}{8 \times 100} = 0.003$$

Spring-roll dielectric elastomer actuator control system response when Ziegler-Nichols PID controller is used;

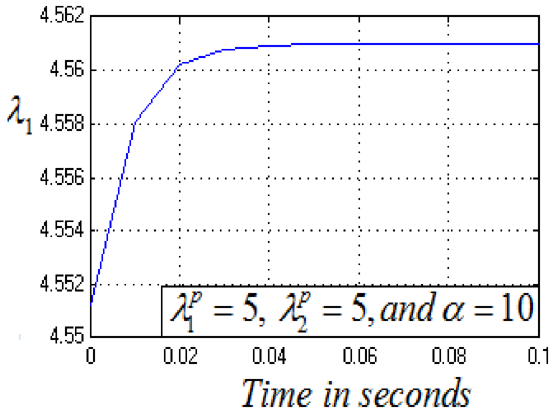


Fig. 10: Step response of the control system using PID controller with $k_p$ =2.4, $k_i$ =480, and $k_d$ =0.003, when dimensionless $P = 0$, and $\lambda_1 = 4.561$

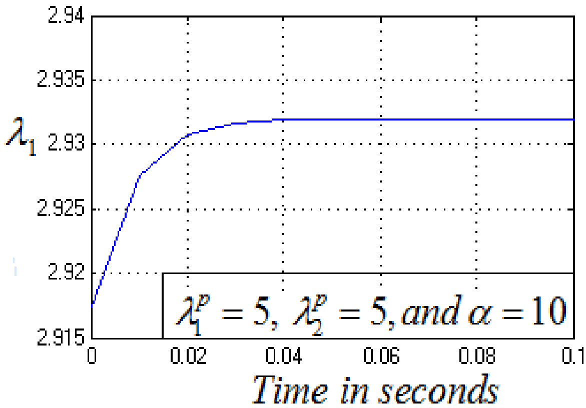


Fig. 11: Step response of the control system using PID controller with $k_p$ =2.4, $k_i$ =480, and $k_d$ =0.003, when dimensionless $P = -18$, and $\lambda_1 = 2.932$

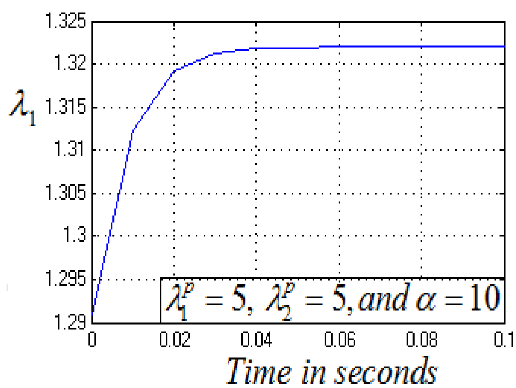


Fig. 12: Step response of the control system using PID controller with $k_p$ =2.4, $k_i$ =480, and $k_d$ =0.003, when dimensionless $P = -36$, and $\lambda_1 = 1.322$

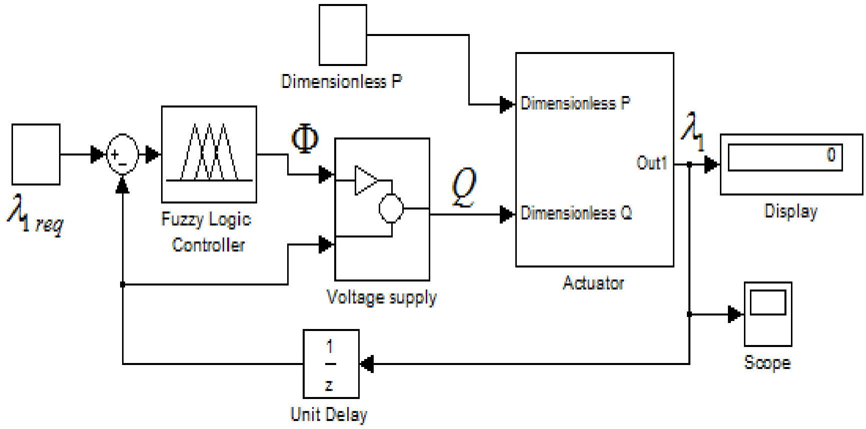


Fig. 13: The simulation of spring-roll dielectric elastomer actuator control system with a fuzzy controller.

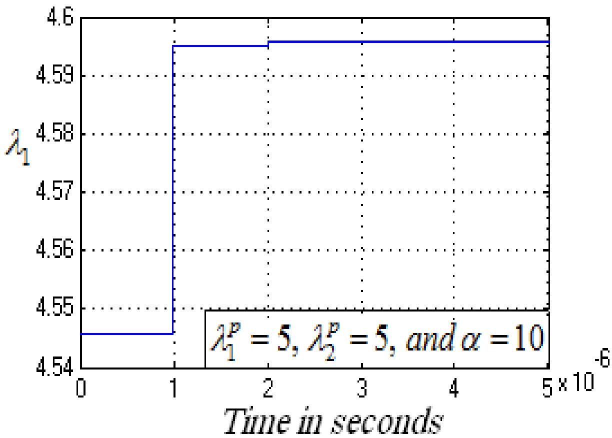


Fig. 14: Step response of the spring-roll dielectric elastomer actuator control system using a fuzzy controller when dimensionless axial force=0, and $\lambda_{1\,req} = 4.561$

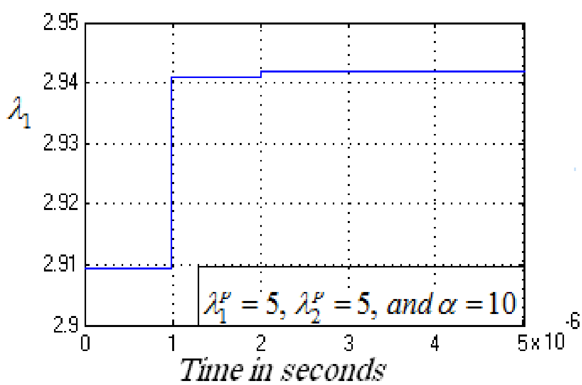


Fig. 15: Step response of the spring-roll dielectric elastomer actuator control system using a fuzzy controller when dimensionless axial force= -18, and $\lambda_{1\,req} = 2.932$

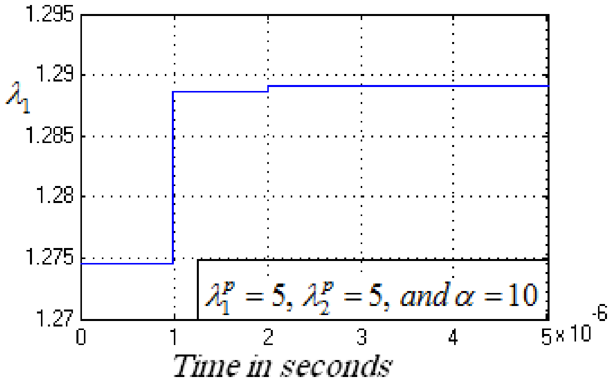


Fig. 16: Step response of the spring-roll dielectric elastomer actuator control system using a fuzzy controller when dimensionless axial force=-36, and $\lambda_{1\,req} = 1.322$

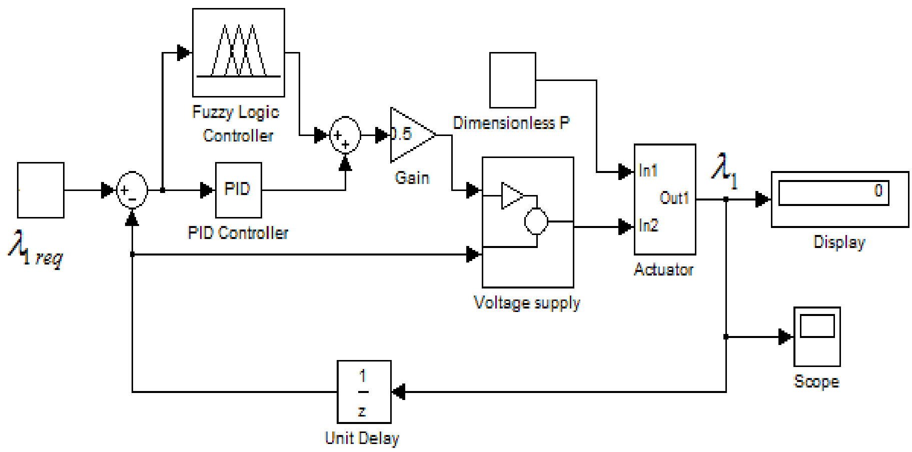


Fig. 17: The simulation of spring-roll dielectric elastomer actuator control system with a fuzzy-PID average controller.

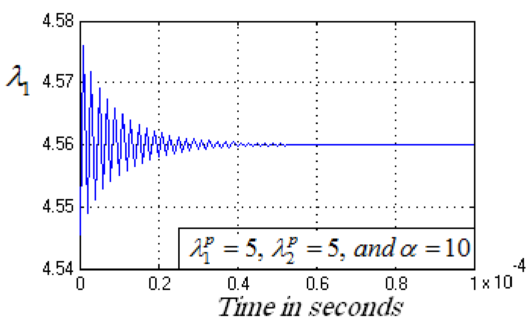


Fig. 18: Step response of the spring-roll dielectric elastomer actuator control system using a PID-Fuzzy average controller when dimensionless axial force=0, and

$$\lambda_{1\,req} = 4.561$$

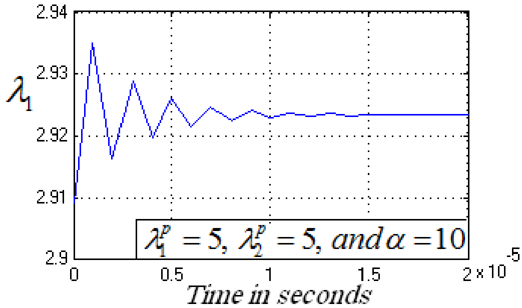


Fig. 19: Step response of the spring-roll dielectric elastomer actuator control system using a PID-Fuzzy average controller when dimensionless axial force= -18, and $\lambda_{1\,req} = 2.932$

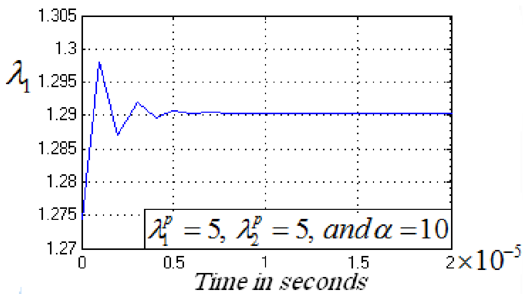


Fig. 20: Step response of the spring-roll dielectric elastomer actuator control system using a PID-Fuzzy average controller when dimensionless axial force=-36, and $\lambda_{1\,req} = 1.322$

In appendix A, a proposed Mat-Lab based software program is used to verify the fitness function required to apply particle swarm optimizing algorithm. In appendix B, another software program is proposed to apply SOA where optimized PID parameters are returned. In this software program the PID parameters obtained from Ziegler-Nichol's controller are used as an initial position.

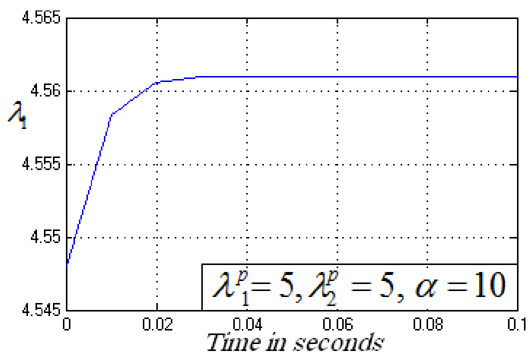


Fig. 21: Step response of the spring-roll dielectric elastomer actuator control system using a BSO based PID controller when dimensionless axial force=0, $\lambda_{1\,req} = 4.561$

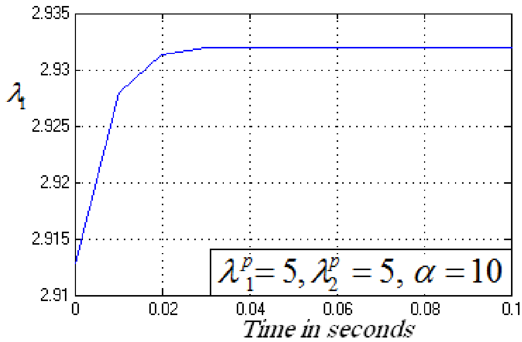


Fig. 22: Step response of the spring-roll dielectric elastomer actuator control system using a BSO based PID controller when dimensionless axial force=-18, $\lambda_{1\,req} = 2.932$

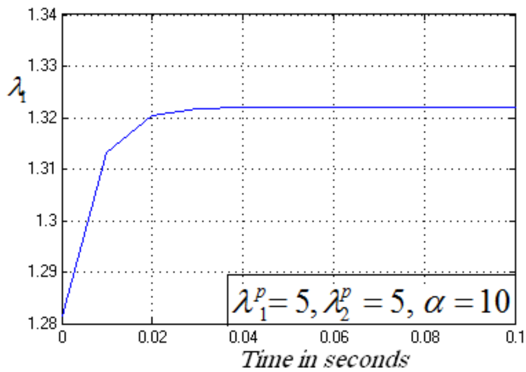


Fig. 23: Step response of the spring-roll dielectric elastomer actuator control system using a BSO based PID controller when dimensionless axial force=-36

The response of different mentioned controllers is listed in Table 1. The choice of the more suitable controller depends upon the application of the actuator itself.

**Table 1: The performance evaluation for the developed controllers**

| | | $E_{ss}$ | $M_p$ | $t_s$ **in seconds** |
|---|---|---|---|---|
| **Ziegler-Nichols PID control** | $P = 0, \lambda_1 = 4.561$ | 0 | 0 | 0.046 |
| | $P = -18, \lambda_1 = 2.932$ | 0 | 0 | 0.04 |
| | $P = -36, \lambda_1 = 1.322$ | 0 | 0 | 0.057 |
| **Fuzzy logic control system** | $P = 0, \lambda_1 = 4.561$ | + 0.031 | 0 | $2\times10^{-6}$ |
| | $P = -18, \lambda_1 = 2.932$ | + 0.010 | 0 | $2\times10^{-6}$ |
| | $P = -36, \lambda_1 = 1.322$ | - 0.033 | 0 | $2\times10^{-6}$ |
| **PID-Fuzzy average control** | $P = 0, \lambda_1 = 4.561$ | - 0.001 | 0.015 | $0.5\times10^{-4}$ |
| | $P = -18, \lambda_1 = 2.932$ | - 0.009 | 0.013 | $10^{-5}$ |
| | $P = -36, \lambda_1 = 1.322$ | - 0.031 | 0.014 | $0.5\times10^{-5}$ |
| **BSO-based PID control system** | $P = 0, \lambda_1 = 4.561$ | 0 | 0 | 0.032 |
| | $P = -18, \lambda_1 = 2.932$ | 0 | 0 | 0.03 |
| | $P = -36, \lambda_1 = 1.322$ | 0 | 0 | 0.036 |

The performance of Ziegler-Nichols PID control system enhanced by optimizing the controller using PSO algorithm (settling time decreased). The performance of fuzzy logic control system enhanced by using PID-Fuzzy average control system (settling time decreased). Slight overshoot appears in case of using PID-Fuzzy average control system due to the gain unit used in that system.

## 6. CONCLUSION

In Spring-roll dielectric elastomer actuator systems, controlling the charges pumped by the voltage supply to the actuator controls its actuation. Different conventional and evolutionary controllers have been developed to control Spring-roll dielectric elastomer actuator. Spring-roll dielectric elastomer actuator fuzzy logic controller is superior in $t_s$ but not superior in $E_{ss}$ whereas BSO-based PID controller is superior in $E_{ss}$ but not superior in $t_s$. Proportional Integral Derivative (PID) controllers are still widely used even though many new control techniques have been proposed.

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# APPENDICES

## Appendix A

function [F]=fitness(kp, ki, kd)
% In the middle of the actuation range, $\lambda_{1req} = 2.932$
T1=tf([214.916*kd 214.916*kp 214.916*ki], [214.916*kd 214.916*kp+214.916 214.916*ki]);
S=stepinfo(T1, 'RiseTimeLimits', [0.1 0.9]);
tr=S.RiseTime;
ts=S.SettlingTime;
Mp=S.Overshoot;
Ess=1/(1+dcgain(T1));
F=(1-exp(-0.5))*(Mp+Ess) + exp(-0.5)*(ts-tr);

## Appendix B

```
function [P, I, D]=optimm(c1, c2, w, n, iter)
x=1;
v=[];
gbest=1;
for i=((n/2)-1): -1: 1
    x(1, i)=2.4-0.2*((n/2)-i);
    x(2, i)=480-2*((n/2)-i);
    x(3, i)=0.003-0.0002*((n/2)-i);
    for j=1:3
        v(j, i)=i*rand;
    end
    pbest(1, i)=x(1, i);
    pbest(2, i)=x(2, i);
    pbest(3, i)=x(3, i);
end
x(1, (n/2))=2.4;
x(2, (n/2))=480;
x(3, (n/2))=0.003;
for i=((n/2)+1): 1: n
    x(1,i)=2.4+0.2*(i-(n/2));
    x(2, i)=480+2*(i-(n/2));
    x(3, i)=0.003+0.0002*(i-(n/2));
    for j=1:3
        v(j, i)=i*rand;
    end
    pbest(1, i)=x(1, i);
    pbest(2, i)=x(2, i);
```

```
      pbest(3, i)=x(3, i);
end
for i=1:n
   kp=x(1, i);
   ki=x(2, i);
   kd=x(3, i);
   F(1, i)=fitness(kp, ki, kd);
end
k=1;
m=1;
fbest=F(1, 1);
while m<n+1
   if fbest>=F(1,m)
      fbest=F(1, m);
      k=m;
   end
   m=m+1;
end
for j=1:3
   gbest(j, k)=x(j, k);
end
for iteration=1:iter
for i=1:n
   for j=1:3
      v(j, i)=w*(n-i)*v(j, i) + c1*rand*(pbest(j, i)-x(j, i)) + c2*rand*(gbest(j, k)-x(j, i));
      x(j, i)=x(j, i)+v(j, i);
   end
   kp1=x(1, i);
   ki1=x(2, i);
   kd1=x(3, i);
   kp=pbest(1, i);
   ki=pbest(2, i);
   kd=pbest(3, i);
   L=fitness(kp, ki, kd);
   P=fitness(kp1, ki1, kd1);
   if P<L
      for j=1:3
         pbest(j, i)=x(j, i);
      end
   end
end
for i=1:n
   kp=pbest(1, i);
   ki=pbest(2, i);
   kd=pbest(3, i);
   F(1, i)=fitness(kp, ki, kd);
end
```

```
m=1;
k=1;
while m<n+1
   if fbest>=F(1, m)
      fbest=F(1, m);
      k=m;
   end
   m=m+1;
end
for j=1:3
   gbest(j, k)=pbest(j, k);
end
end
P=gbest(1, k);
I=gbest(2, k);
D=gbest(3, k);
```

## استخدام طرق التحكم التقليدية والحديثة للتحكم فى مشغلات الإلاستومر العازل الملفوف على زنبرك

للتحكم فى مشغلات الإلاستومر العازل الملفوف على زنبرك يلزم أولاً معرفة قيمة الاستطالة التى يجب للمشغل أن يستطيلها كما يجب معرفة قيمة الحمل الذى يحمله هذا المشغل.

والاستطالة المطلوبة من المشغل هى النقطة المرجعية لنظام التحكم ويستخدم ويستخدم فى هذا البحث عدد من أساليب التحكم التقليدية والحديثة: نظام التحكم التناسبى – التكاملى – التفاضلى ، نظام تحكم المنطق المبهم ، نظام تحكم متوسط النظامين السابقين ، ونظام التحكم التناسبى – التكاملى – التفاضلى بعد جعله مثالياً بواسطة لوغاريتم سرب الجسيمات.

وقد تم تقييم أداء نظم التحكم المقترحة بدلالة: خطأ الحالة المستقرة ، القيمة العظمى للتجاوز ، والزمن اللازم لاستقرار نظام التحكم.

وللتحكم فى استطالة هذا النوع من المشغلات يجب التحكم فى جهد المنبع الذى يغذيها ، الذى يتحكم بدوره فى استطالة المشغل وفى هذا تستخدم نظم تحكم ذو تغذية عكسية أحادية.

وفى هذا البحث تم استنتاج استجابة كل نظام تحكم حيث يتم اختيار النظام المناسب بحسب التطبيق المطلوب ، فبعض التطبيقات تحتاج لأن يكون خطأ الحالة المستقرة مساوياً للصفر والبعض الآخر يحتاج إلى استجابة سريعة.

تم تصميم مشغلات الإلاستومر العازل الملفوف على زنبرك ونظم التحكم السابقة بناء على بارمترات التصميم المثالية والتى تم استنتاجها فى [1، 2].

أثبتت النتائج أن نظم التحكم المقترحة قوية وفعالة وتدعم هذا النوع من المشغلات عند استخدامها كوحدة بنائية للعضلات الأصطناعية.