Corrigendum: System identification based PSO approach for networked DC servo motor (2021 IOP Conf. Ser.: Mater Sci Eng. 1090 012059)

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Page 1:
In the published paper:
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It should read
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Page 4:
In the published paper the equation of e appear like: e= ( p - r)

It should be: e = (θᵢ - θᵣ)

Page 5:
Appeared in the published paper as
\[ V_i(t + 1) = X_i(t) + V_i(t + 1) \]
(16)
\[ γ = C_1 + C_2. \]
(18)

It should appear like:
\[ V_i(t + 1) = X_i(t) + V_i(t + 1) \]
(16)
\[ γ = C_1 + C_2. \]
(18)
equation 19 appeared

\[ F_1 = \sum_{i=1}^{\infty} \sqrt{\theta_p^2(i) - \theta_m^2(i)} \times T_x \]

(19)

The corrections:

\[ F_1 = \sum_{i=1}^{\infty} \sqrt{\theta_p^2(i) - \theta_m^2(i)} \times T_x \]
\[ \Theta_0 = \frac{0.4029}{0.3920s^2+0.7054s +0.0110} \]

or

\[ \Theta_0 = \frac{1.0278}{s^2+1.7994s +0.02806} \] (20)

**Page 10:**

In the published paper, the equation number of eq.21 also was not at the same line:

\[
\text{accuracy} = 100 - \frac{\sum_{i=1}^{N} (\Theta_i^2(i) - \Theta_u^2(i))}{\sum_{i=1}^{N} (\Theta_i^2(i))}
\] (21)

Correction:

\[
\text{accuracy} = 100 - \frac{\sum_{i=1}^{N} (\Theta_i^2(i) - \Theta_u^2(i))}{\sum_{i=1}^{N} (\Theta_i^2(i))}
\] (21)

**Pages 11, 12 and 13:**

In the published paper, figure 13 (The proposed Simulink model of fuzzy PID controller) was presented by mistake.

It appears:

This figure in the mentioned picture should be corrected to be figure 14 not 13, so the figures 13 to 17 should be modified as below: (there is a mixing up in the figures)
Figure 13. The proposed Simulink model of fuzzy PID controller.

Figure 14. Fitness function behaviour with iterations for formula 19.

Figure 15. Angular position response of the modelled system designed by fuzzy PID controller tuned by PSO using formula 19.
Figure 16. The fitness function of the simulated system using PSO for best parameters of the FLC of equation (22).

Figure 17. Angular position response of the modeled system designed by fuzzy PID controller tuned by PSO using formula 22.

Page 12:

F1 and F2 appear in the following text as:

The results prove the importance of presence the overshoot in the equation as in formula (22), and table 4 shows a comparison between the results of formulas $F_1$ and $F_2$.

They should be:

The results prove the importance of presence the overshoot in the equation as in formula (22), and table 4 shows a comparison between the results of formulas $F_1$ and $F_2$. 
Page 13:

In section 6, theta symbol in the posted paper in this page also not appear, and it shows like:

1. Taking the same model of equation (20) and scaling factors of equation (22).
2. Using TrueTime simulator to calculate the output response ($\Theta_{mn}$) of the model system with the wireless network.
3. The output response ($\Theta_{mn}$) evaluated under the simulated wireless network is expected to be highly affected by the time delay introduced by the network.
4. Same procedure used to evaluate the model system ($\Theta_m$) in figure 5 (part 1), will be used to estimate the time delay in the wireless network $C_{sr}$ (between sensor and controller) and $C_{cr}$ (between controller and actuator).

The corrections are:

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4. Same procedure used to evaluate the model system ($\Theta_m$) in figure 5 (part 1), will be used to estimate the time delay in the wireless network $C_{sr}$ (between sensor and controller) and $C_{cr}$ (between controller and actuator).
System identification based PSO approach for networked DC servo motor

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Abstract. Networked control system (NCS) suffers from inherent time delay and packet loss associated with any communication network. To build a controller that overcomes these issues, we need to know the accurate model of the system a priori. But, unfortunately most of the practical systems faced with lack in available and complete specifications of the physical system that helps in developing accurate mathematical model. This paper provides an experimentally identification method for any system based on Particle Swarm Optimization approach. The objective function to be minimized is based on the integral squared error criterion between the experimental and modeled trajectories. An armature-controlled DC motor with gearbox in lab is examined. The practical system trajectory represents the angular rotation of the output shaft. The DC motor system is modeled and controlled using fuzzy PID controller by the presented approach. Experimental results show that model equation has been successfully found with 94% accuracy. Also, a methodology for modeling the time delay in WNCS is presented.

1. Introduction

Nowadays, the use of wireless networks have been increased according to a lot of features that its offered compared with wired networks such as low cost, security and freedom of movement[1]. Wireless networked control systems (WNCSs) consist of dynamic plant (such as motor, robot, or vehicle) to be controlled, sensor nodes, a distributed remote controller which receive the measurements of the sensors and send the control signals, and actuators to receive the control signals and actuate the plant, these nodes are connected together by wireless networks[2] as seen in Figure 1. Using of Wireless networked control systems (WNCS) came to eliminate Networked Control Systems (NCS) problems such as: limitations in flexibility and mobility that back to wire connections of network, Furthermore, packet loss and time delay which they mainly effect on system performance and instability[3]. In spite of the benefit of wireless technology but the main disadvantages are the delay between the controller and sensors/actuators nodes as soon as the packet loss which are effect on system instability[4]. Researchers have been using NCS and WNCS architectures with different plants with addition of time delay compensation, such as the work in [5] presented a new Fuzzy-PID like-Gain Scheduling controller for Ethernet 802.3 in NCS and Discussed the problem of time delay that effecting on stability of NCS. Mohamed Abdelbar in [6] proposed the design and implementation of four different advanced control techniques for Speed Control of the Performance of Brushless DC Motor. Ivan, et. al in [7] studied how stability of NCS are changed under different values of time delay and packet loss, and Mais in [3] and Aparna, et al. in [8] used Sliding Mode variable structure controller (SMC) and examined the system performance by changing the loss probability compared with PID controller, also both Mais and Ivan in [3,7] sequentially, used DC motor over NCS representing by ZigBee network. Russel, Abdullah, Rasha, et al. in [4]-[9],[10] sequentially, proposed Fuzzy Logic Controller (FLC) based PID (FLC-PID) and compared it with the conventional PID controller to controlling the speed of DC motor, where both works in [4]-[10] controlled the speed of a stepper motor but over different networks which they are Wi-Fi and ZigBee networks.
Sequentially using Particle Swarm Optimization (PSO) technique, but Abdullah in [9] proved that the FLC-PID controller which is tuned by genetic algorithm (GA) improved the reference command speed tracking and sudden load changes disturbance rejection for the DC motor model.

In WNCS we need to work with True Time simulator to consider a controller in remote node control the plant which is here gear box DC motor in our lab, unfortunately the mathematical model of this motor is unknown, so this paper focused on system identification by finding the transfer function of the gear box DC motor in a way of Particle Swarm optimization technique, furthermore optimize the parameters of fuzzy PID controller. The paper is structured as follows: section 2 describes Mathematical Model of Armature DC Motor, section 3 introduces the controller design, section 4 presents system identification procedure, section 5 introduce optimization of fuzzy PID controller with Particle Swarm Optimization (PSO) technique, section 6 presents the methodology of estimation the time delay in WNCS and finally, section 7 summarizes the conclusion of the paper.

2. Mathematical Model of Armature DC Motor
DC motors are machines that transform electrical energy into mechanical energy, causing a rotary movement. DC motors are used in a lot of applications and devices and it's utilized when wide changes in speed were required. The dc motors are driven by a dc power source [11]. There is a lot of advantages of using DC motors over AC motors such that DC motor more controllable than the other types, they have fixed torque, can supply accurate position control, yield less heat, higher efficiency, in addition, it requires simpler controllers [9]. The DC motor uses electricity and a magnetic field to produce torque, which makes it to turn. It ordered an electric coil works as an electromagnet and two magnets of opposite polarity. The repellent and attractive electromagnetic powers of the magnets supply the torque that makes the motor to turn. besides, it consists of armature winding (one set of coils), inside a set of permanent magnets, called the stator. the motion results by applying a voltage to the coils produce a torque in the armature[12].

![Figure 1. Block diagram of a WNCS.](image1.png)

![Figure 2. Full equivalent circuit of Armature Controlled DC Motor.](image2.png)
Figure 2 shows the circuit of the armature controlled DC motor where \( u \) is the armature input voltage, \( \omega \) is the angular velocity, \( R_a \) the resistance of the armature, \( L_a \) is the inductance of the armature winding, \( i_a \) the armature current, \( e_b \) is the back emf, \( T_{motor} \) is the torque, \( J \) is the equivalent moment of inertia of motor shaft and load referred to the motor, and according to [12] the system transfer function can be derived as follow:

\[
u = R_a i_a + L_a \frac{di_a}{dt} + e_b \quad (1)
\]

\[
T_{motor} = K_t i_a \quad (2)
\]

where \( K_t \) is the torque constant.

likewise, in [12] defined the voltage represented by the speeds mathematically as:

\[
e_b = K_p \omega \quad (3)
\]

where \( K_p \) is the velocity constant.

By Combining previous equations, the mathematical model of the motor can be derived as follows:

\[
L_a \frac{di_a}{dt} + R_a i_a + K_b \omega = u \quad (4)
\]

\[
j \dot{\omega} + B \omega = K_t i_a \quad (5)
\]

Taking Laplace transform of the system’s differential equations with zero initial conditions gives:

\[
(sL_a + R_a)I_a(s) + K_b \Omega(s) = U(s) \quad (6)
\]

\[
(sJ + B)\Omega = K_t I_a(s) \quad (7)
\]

Eliminating \( I_a \) yields the input-output transfer function:

\[
\frac{\Omega(s)}{U(s)} = \frac{K_t}{sL_a^2 + (sR_a + BL_a)s + BR_a + K_tK_b} \quad (8)
\]

\( L_a \) can be negligible as normally being a very low value, then equation (8) will be reduced to the following equation:

\[
\frac{\Omega(s)}{U(s)} = \frac{K_t}{as + b} \quad (9)
\]

where \( a = (JR_a + BL_a), \quad b = BR_a + K_tK_b \)

The relation between motor angular speed and angular position is given by:

\[
\omega = \frac{d\theta}{dt} \quad (10)
\]

By taking the integration for both sides with Laplace transform of equation (10) yields:

\[
\theta(s) = \frac{\Omega(s)}{s} \quad (11)
\]

Likewise, the relation between armature input voltage and the angular position can be expressed as:

\[
U(s) = K_r \quad (12)
\]

where \( K_r \) is the voltage-displacement constant.

The mathematical equation of the gear in motor initialize as:

\[
K_g = \frac{N_D}{N_R} \quad (13)
\]

Where \( N_D \) is the number of teeth in chain ring, \( N_R \) is the number of teeth in rear cog.

By combining equations (9), (11), (12) and (13) the general input-output transfer function:

\[
\frac{\Omega(s)}{r(s)} = \frac{K}{as^2 + bs + c} \quad (14)
\]

where \( K = K_R \times K_t \times K_g \)
3. Controller Design

3.1 Fuzzy PID controller

Fuzzy PID controllers are proved to perform efficiently with DC motors system in comparison to the classical PID controllers\cite{13}\cite{14}\cite{15}. Fuzzy logic controllers is an alternative to PID controller and referred as an intelligent control\cite{16}. Fuzzy PID controller offers better controlling due to its characteristics on systems have produce a good dynamic response, rising time, overstrike and robustness\cite{6}. Fuzzy logic (FL) is a type of soft computing that start in 1965 by Lutfi A. Zadeh\cite{5}. FLC depending on knowledge of human thought to represent the crisp values and deals with the issues that have uncertainty, vagueness and use membership functions (MF) with values varying between 0 and 1. In general, fuzzy inference system applied three sequential steps: fuzzification of input data, fuzzy inference, and defuzzification of output data as shown in figure 3. fuzzification means convert the input data of crisp values to fuzzy values using the membership function. Step two is fuzzy inference system (FIS) consists of fuzzy rules that can be evaluated in rule base represented by a number of (IF-THEN). Table 1 shows the rule base of FLC where the linguistic variable $e = \left( p - r \right)$, also the linguistic values NB is the negative big, NM is the negative medium, NS is the negative small, PB is the positive big, PM is the positive medium, PS is the positive small and Z is zero. figure 4 shows the membership function type that used in this work. There are two types of fuzzy inference:

1. Mamdani fuzzy model: where both premise value and consequent are fuzzy.
2. Takagi-Sugeno fuzzy model: where the premise is fuzzy, and consequent is crisp fixed or a linear function of the inputs.

The result of each rule will be combined to enter defuzzification. Defuzzification is the last step that convert the output of fuzzy data to non-fuzzy values depending on which method type of defuzzification used, and these types are: Center of gravity, Mean of maximum, First maximum, and Last maximum\cite{5,17}.

![General structure of FL controller.](image)

**Figure 3.** General structure of FL controller.

**Table 1.** The Table of Fuzzy Rule

| $e$  | NB | NM | NS | Z  | PS | PM | PB |
|------|----|----|----|----|----|----|----|
| NB   | NB | NB | NB | NB | NM | NS | Z  |
| NM   | NB | NB | NB | NB | Z  | PS |
| NS   | PB | NM | NS | Z  | PS | PM |
| Z    | NS | Z  | PS | PM | PB |
| PS   | NM | Z  | PS | PM | PB |
| PM   | NS | Z  | PS | PM | PB |
| PB   | Z  | PS | PM | PB |

\[\text{e} = \left( p - r \right)\]
3.2 Particle Swarm Optimization (PSO)

In 1995, Kennedy and Eberhart developed Particle Swarm Optimization (PSO) as an effective method in optimization problems. The goal of PSO method is taking animal behavior to looking for the closest locations to global minimum or maximum solutions. The PSO algorithm simulate social behavior by using a population called swarm. Each swarm has an individual called a particle. Each particle acts a position or solution to the problem. In every iteration, particles update position to find the best solution[18]. PSO offers many advantages like simplicity in calculations, it is an autotuning method so there is no need to mathematical calculation process. The particles update its positions based on equations below[4]:

\[
V_i(t + 1) = wV_i(t) + C_1r_1(P_i(t) - X_i(t)) + C_2r_2(G - X_i(t)) \tag{15}
\]

\[
V_i(t + 1) = X_i(t) + V_i(t + 1) \tag{16}
\]

Where \(w\) is the inertia weight, \(C_1\) is cognitive learning factor, \(C_2\) is social learning factor, \(r_1\) and \(r_2\) are uniformly generated random numbers in the range of \([0,1]\), and \(P_i\) is the best solution of \(i^{th}\) particle.

In a way to improve the response of DC motor system, PSO algorithm used with two MATLAB programs in this paper, first one to find equation parameters that present by \(k, a, b,\) and \(c\), and the second one used to find the optimal values for the controller parameters \(k_1, k_2, k_3\) and \(k_4\). The inertia weight \(w\) based on a code developed by Korani[19] is given by:

\[
w = \frac{2}{[1 - \sqrt{\gamma^2 - (4\gamma)}]} \tag{17}
\]

where \(\gamma\) is a variable used to adding the value of cognitive learning factor \((C_1)\) to social learning factor value \((C_2)\) and as the formula:

\[
\gamma = C_1 + C_2. \tag{18}
\]

The code was tested for the problem at hand and gives very good results compared to other trial and error selections.

4. Hardware circuit design with its simulation in MATLAB

The methodology shown in figure 5 is set for single-input single-output linear system with unknown mathematical model for WNCS require two parts. First part is the identification of system model which is presented earlier in section 2, and second part is the estimation of time associate with the wireless network.
In this work, an armature-controlled DC motor with a gearbox that has unknown mathematical model has been used as an example of the system model. Also, by testing in our lab the results of used open-loop or close loop system without a controller approved the system remain unstable, and because fuzzy PID controller is better than the traditional PID controller based on the reasons mentioned before, so a fuzzy PID controller is proposed in this paper to work with it. Thus, to identify the mathematical model of gearbox DC motor according to equation (14) there are two parts: hardware design part and identification part, as follow:

4.1 hardware part

The practical circuit consists of a group of counters which can be express as one D flip-flop used for saving data, two AND gates, and three IC’s counters, push-button switch used for reset the counters, DC gear box motor, LEDs, L298 driver circuit, nano capacitors, Arduino mega, wires, also Vero board, as shown in figure 6.
Figure 6. Hardware circuit design in LAB.

The circuit works after the control signal feedback from MATLAB using Arduino mega where it’s used as interface card, then D-Flip-flop is used to convert the two phases of each incremental shaft encoder, (A and B), to read the clock wise (CW) and counter clock wise (CCW) directions. The Two AND gates are used to convert the direction into input pulses to the up/down counter. DC-motor with gear box as shown in figure 7, contain a sensor with 4000 pulses as maximum so three IC’s with 4-bit counters are needed for the encoders of 1 Amp motor to cover the pulses, also the sensor rotates 99 times until it achieves one complete cycle.

Figure 7. DC-motor with gear box in LAB.

In this study, Figure 8 shows the model part of the practical circuit with MATLAB program where pins from 22 to 44 considered as digital input pins that equal to pins in practical circuit. The signal back from low pass filter and enter as a negative feedback with a desired input (which is here step input with a positive half sinewave) to gains of $k_0$ and $k_1$ to computing the error, then goes to the PD fuzzy controller that used 5 membership functions with Mamdani model and triangle shape. Finally Control signal goes to the practical circuit using pulse width modulation (PWM).
8

Figure 8. Simulation of Practical work in MATLAB.

The result is shown in figure 9, where it clarifies the behavior of the output with the input step, in addition, the result of $\Theta_P$ (output of practical system simulation) response with the simulation time have been saved as a table to be used in next part.

Figure 9. Angular position response of $\Theta_P$ (—) for actual system when the input is $\Theta_r$ (—).

4.2 identification method

The way of identification depends on minizine the error, this paper focus on minizine the integral square error. At first the output of real part with the simulation time have been saved as a table of points, then to compare the result of real part in order to get nearest scaling factors and calculate the DC motor equation, MATLAB program with PSO optimization technique have been applied as seen in Figure 10. In addition to the parameters that mentioned in table 2 that consider as a best parameter that been used after trial and error technique results for using in this work, same sample time used for both parts and equal to 0.01, the Root Mean square error is used for evaluating the fitness function as shown in equation below:
\[ F_1 = \sum_{i=1}^{N} \sqrt{\theta_p^2(i) - \theta_m^2(i)} \times T_s \]  

(19)

Where \( \theta_p \) is the angular position of the motor for practical system, \( T_s \) is the sampling time and \( \theta_m \) is the angular position of the modeled system.

### Table 2. PSO parameters for equation calculation

| Parameters       | Value |
|------------------|-------|
| number of birds  | 60    |
| Birds steps      | 60    |
| Dimension of the problem | 4     |
| \( C_1 \)        | 3.5   |
| \( C_2 \)        | 3.5   |

After simulation, the result of PSO technique shows the best parameters for the DC-motor model are \( k = 0.4029 \), \( a = 0.3920 \), \( b = 0.7054 \) and \( c = 0.0110 \), with the best fitness function is 9.2088 as shown in figure 11, in addition to the equation (14) they yield the transfer function:

\[
\frac{1}{2} = \frac{0.4029}{0.3920^2 + 0.7054s + 0.0110}
\]

or

\[
\frac{1}{2} = \frac{1.0278}{s^2 + 1.7994s + 0.02806}
\]

Equation (20) is considered as DC-motor modeled with a gear box equation to be used later with fuzzy PID controller for controlling the whole network.

![Proposed Simulink system for modeled DC motor.](image-url)
Figure 11. Fitness function behavior for equation 20 using PSO.

Figure 12. Angular position response of $\theta_p$ for actual system with the angular position of the modeled $\theta_m$ system using PSO.

The accuracy of figure 12 result has been calculated based on the equation below:

$$accuracy = 100 - \frac{\sum_{i=1}^{N} (\theta_p^i(0) - \theta_m^i(0))^2}{\sum_{i=1}^{N} (\theta_p^i(0))^2}$$

(21)

Where $N$ is the ratio between the final time the sampling time. The result of equation (21) shows that the accuracy between the actual and modeled systems reached 94%.

5. Optimization of fuzzy PID controller parameters
PSO optimizer intent to determine the right fuzzy rules that can set the output to build on it so that PID can interpret the best scaling factors \( (k_1, k_2, k_3, \text{ and } k_4) \). where the Transfer function that is chosen same in (20) and PSO parameters same as seen in table 3 which are considered as best parameters that been used after trial and error technique results for using in this work with fitness formulas:

1. \( F_1 \)

2. \( F_2 = \sum_{i=1}^{N} \sqrt{\Theta_p^2(i) - \Theta_m^2(i)} \times 0.95 + (\text{sys.overshoot} \times 0.005) \times T_s \) \( (22) \)

Figure 13 shows the Simulink model, and figure 14 shows the fitness function of the simulated system using PSO for best parameters of the FLC of equation (19) which they are: \( k_1 = 1.0961, \ k_2 = 0.0003, \ k_3 = 1.0897, \) and \( k_4 = 83.7493 \), with best fitness function equal to 71.0969. Figure 15 shows the simulated result.

| Parameters                  | Value |
|-----------------------------|-------|
| number of birds             | 35    |
| Birds steps                 | 85    |
| Dimension of the problem    | 4     |
| \( C_1 \)                   | 2.5   |
| \( C_2 \)                   | 2.5   |

**Table 3.** PSO parameters for controller parameters calculation

**Figure 13.** The proposed Simulink model of fuzzy PID controller
Figure 14. Fitness function behavior with iterations time for formula 19.

Figure 15. Angular position response of the modeled system designed by fuzzy PID controller tuned by PSO using formula 19.

Figure 16 shows the fitness function of the simulated system using PSO for best parameters of the FLC of equation (22) which they are: $k_1 = 1.02639$, $k_2 = 0.1136$, $k_3 = 0.0817$, and $k_4 = 189.5030$, with best fitness function equal to 6.6910. Figure 17 shows the simulated result optimized the dynamic performance of the system. The optimized FLC will be used in the networked system using TrueTime network simulator. The results prove the importance of presence the overshoot in the equation as in formula (22), and table 4 shows a comparison between the results of formulas F_1 and F_2.
Figure 16. The fitness function of the simulated system using PSO for best parameters of the FLC of equation (22)

Table 4. Scaling factor parameters tuned by PSO for the modeled system showing the characteristics.

| Fitness function | Parameters | Dynamic Characteristics |
|------------------|------------|------------------------|
| $F_1$            | $K_1 = 1.0961$, $K_2 = 0.0003$, $K_3 = 1.0897$, $K_4 = 83.7493$ | RMSE = 71.0969, Overshoot = 11.1731, Rise Time = 0.3728, Settling Time = 3.9346 |
| $F_2$            | $K_1 = 1.0239$, $K_2 = 0.1136$, $K_3 = 0.0817$, $K_4 = 189.5030$ | RMSE = 6.6910, Overshoot = 0.1429, Rise Time = 0.8782, Settling Time = 1.1665 |

6. the proposed methodology of estimating the time delay in WNCS
With the same approach that used in this work, the estimation of the time delay in WNCS can be summarized as follows:
1. Taking the same model of equation (20) and scaling factors of equation (22).
2. Using TrueTime simulator to calculate the output response ($\theta_{\text{sys}}$) of the model system with the wireless network.
3. The output response ($\theta_{\text{sys}}$) evaluated under the simulated wireless network is expected to be highly affected by the time delay introduced by the network.
4. Same procedure used to evaluate the model system ($\theta_{\text{sys}}$) in figure 5 (part 1), will be used to estimate the time delay in the wireless network $C_{\text{sc}}$ (between sensor and controller) and $C_{\text{ca}}$ (between controller and actuator).
5. The overall system will apply practically in LAB where the controller node will assume to be a remote node and will control the plant which is DC motor. This section is left for a future work to be continued by the authors.

7. Conclusion
To build a controller that overcomes WNCS issues, the accurate model of the motor needs to be known. Unfortunately, most of practical systems faced with lack in available and complete specifications of the physical system that helps in developing accurate mathematical model. This paper devised a test method using hardware circuit design for identification to find the equation of DC-motor with gear box found in our lab. The presented identification methodology used to model the DC-motor is successfully found to be within 94% accuracy. The FLC scaling factors after PSO tuning of the modeled system is found to be $k_1 = 1.02639$, $k_2 = 0.1136$, $k_3 = 0.0817$, $k_4 = 189.5030$. The
tuned FLC will be used in practical network to control the DC-motor, and this is currently a new work initiated by the authors.

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