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A Nonlinear Neural Controller Design for the Single Axis Magnetic Ball Levitation System Based on Slice Genetic Algorithm

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ABSTRACT

This paper presents a ball position tracking control tuning algorithm for single axis magnetic levitation system using slice genetic optimization technique based nonlinear neural controller. As simple and fast tuning technique, slice genetic optimization algorithm is used to tune the nonlinear neural controller's parameters in order to get the best control action for the magnetic levitation system through the tracking of pre-defined location of the steel ball. Pollywog wavelet activation function is used in the structure of the nonlinear neural controller. The obtained results (using MATLAB program) show that the effectiveness of the proposed controller in minimizing the tracking error to zero value and also, in the softness of the control action with the lowest amount of fitness evaluation number.

Keyword: Magnetic Levitation System; Neural Controller; Slice Genetic Algorithm.

تصميم مسيطر عصبي لاخطي لنظام تعليق الكرة المغناطيسية احادية الأتجاه مبني على اساسة خوارزمية الشرائح الجنية

الخلاصة

ان هذا البحث يقدم خوارزمية تنغيم المسيطر تتابع موقع كرة لنظام التعليق المغناطيسي احادي الأتجاه بستخدام تقنية الشرائح الجنية الأمثلية اساسها المسيطر العصبي اللاخطي.

لقد تم استخدام خوارزمية الشرائح الجنية لانها تقنية سهلة و سريعة في تنغيم عناصر المسيطر العصبي اللاخطي لكي يحصل على افضل فعل للمسيطر لنظام التعليق المغناطيسي من خلال تتابع الموقع المعرف مسبقا لكرة الأستيل. ان الدالة الفعالة (Polywog Wavelet)استخدمت في هيكلية المسيطر العصبي اللاخطي.

لقد تم الحصول على النتائج بأستخدام الحقيبة البرمجة ماتلاب وتبينت فعالية المسيطر المقترح في تقليل الخطأ التتابعي الى قيمة الصفر وكذلك فينعومة فعل المسيطر مع اقل عدد ممكن لأستدعاء دالة التقيم.

INTRODUCTION

Recently, increasing amount of study on the topic of magnetic levitation system has attracted significant consideration in different industrial and engineering applications, such as; fast train, frictionless bearing and vibration isolation systems [1]. These applications need that the magnetic levitation systems have the capability to follow the particular maglev path stably.

In order to solve the stabilization problem that has come close to the problems of maglev control, many studies and works have been done, because it has nonlinear dynamic behaviour, speedy and unstable behaviour in the open loop response of the steel ball position system [2]. For that reasons, several control algorithms have been proposed in the literature in position-

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tracking control problems, such as fuzzy logic PID controller [3], robust nonlinear controller [4], cognitive nonlinear controller [5], back-stepping with sliding mode controller [6], sliding model controller [7], and intelligent controller based on genetic algorithm [8].

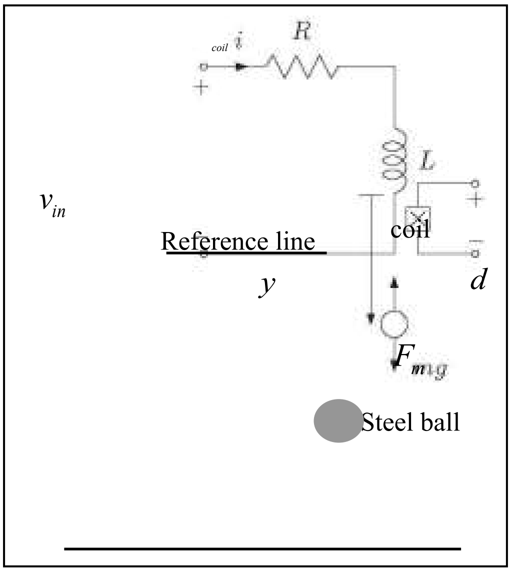
The main contribution of this paper is in using the slice genetic algorithm to find the optimal neural controller parameters and also, to reduce the number of function evaluation. Moreover, slice genetic algorithm has the ability to minimize the population size and reduce the number of iterations through generations.

Although, the presence of bounded disturbances through generations, the proposed controller shows the effectiveness and produce the optimal control action that reduced the tracking error as shown in the simulation results.

The paper is ordered as follows: a brief introduction of the mathematical model of the magnetic levitation system has been presented in section two. The proposed neural controller is described in section three based on slice genetic algorithm. The simulation results have been shown in section four. The final part of the work and the conclusions are given in section five.

Single Axis Magnetic Ball Levitation System

Figure (1) presents the schematic diagram of the single-axis magnetic levitation system [5], which could be divided into two systems: electrical and mechanical.



Figure(1). Schematic diagram of the single axis magnetic ball levitation system [5].

The electrical system has a single electromagnetic coil inductance and resistance L and R respectively. Equation 1 shows the differential equation as below:

$$v_{in}(t) = Ri(t) + L\frac{di(t)}{dt} \quad \ldots \quad (1)$$

Where

i : Electromagnetic current control signal.

v_{in} : Input voltage signal.

The mechanical system simply presents by defining the force that result from the electromagnet activity to the steel ball as shown below in equation 2:

$F_a = F_g - F_m$ … (2) where

F_a : Acceleration force.

F_m : Electromagnetic force.

F_g : Gravity force.

The electromagnetic force can be described as a nonlinear equation (3) [5 and 9].

$$F_m = k_f\left(\frac{i}{y^3}\right) \quad \dots (3)$$

where

k_f : Magnetic force constant.

y : Ball distance from magnetic.

Using Newton's second law, the magnetic levitation system based on electromagnetic attraction characterize by the non-linear and unstable open-loop dynamics relating to the ball position and the coil current, as follows:

$$\ddot{y}m = mg - k_f \frac{i}{y^3} \quad \dots (4)$$

where

m : Mass of steel ball.

g : Gravitation constant.

During the steady-state the velocity $\dot{y}$ and acceleration $\ddot{y}$ of the ball are equal to zero. Therefore, equation (4) becomes as shown below:

$$i_{ss} = \frac{mgy_{ss}^3}{k_f} \quad \dots (5)$$

Where

i_{ss} : is the value of electromagnetic coil current at the steady-state.

y_{ss} : is the ball position constant.

Table 1 shows the parameters of the magnetic levitation system at the ball desired position equivalent to 2cm are given below:

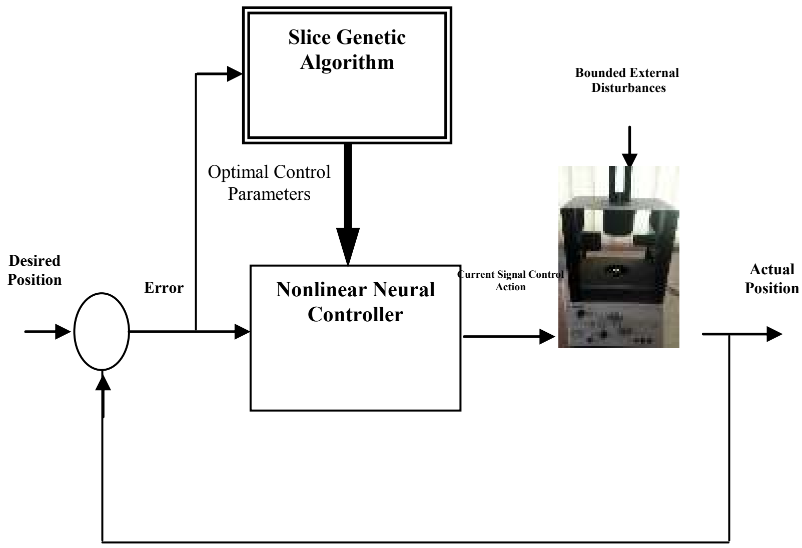
Table (1): Parameters of the magnetic levitation system [5].

i	**Coil Current**	1.045 A
V_{in}	**Input Voltage**	1.787 V
y_d	**Desired Distance in volt.**	3.866 V
m	**Mass of Ball**	0.0413 kg
k_f	**Magnetic Force Constant**	3.1×10^{-6} kg.m^5/s^2/A
g	**Gravitation Constant**	9.81 m/s^2
R	**Coil Resistance**	1.71 Ω
L	**Coil Inductance**	15.1 mH
w	**White Noise Value**	±0.01 V

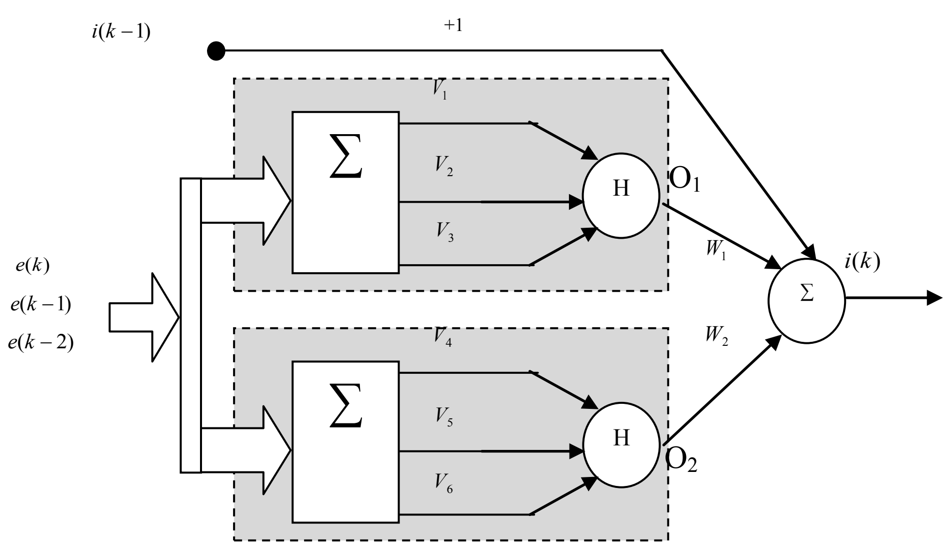
Nonlinear Neural Controller Design

Figure (2) describes the block diagram of the proposed structure of the nonlinear neural controller. The approach to control the ball position of magnetic levitation system depends on the available information of the unknown nonlinear model can be known by the input-output data and the control objectives.

The slice genetic algorithm will generate the optimal parameters for the nonlinear neural controller in order to obtain the best current control signal that will minimize the position tracking error of the ball magnetic levitation system in the presence of external disturbance. In general, the feedback controller is very important because it is necessary to stabilize the tracking error of the system when the actual output of the system drifts from the desired point, therefore; the proposed nonlinear neural controller for the nonlinear SISO magnetic levitation system can be shown in Fig. 3.

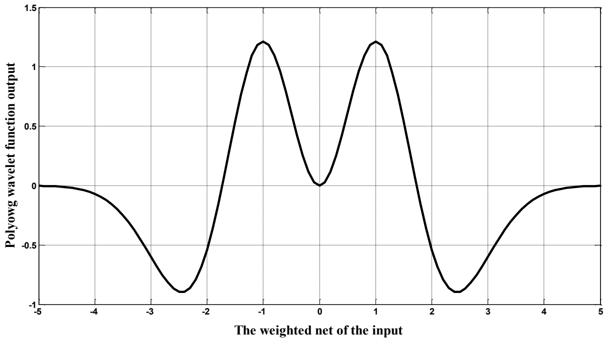


Figure(2). The proposed nonlinear neural controller structure for single axis magnetic ball levitation system.



Figure(3). The proposed nonlinear neural controller structure.

The control structure has the characteristics of strong adaptability, good dynamic characteristic and robustness because it is based on neural networks with non-linear Polywog wavelet activation functions [10], as shown in Fig. 4.



Figure(4). Polywog wavelet function.

The proposed nonlinear adaptive control law based on neural network technique as follows:

$$net_1(k) = V_1[e(k) - e(k-1)] + V_2 e(k) + \quad V_3[e(k) - e(k-1) + e(k-2)] \qquad \text{... (6)}$$

$$net_2(k) = V_4[e(k) - e(k-1)] + V_5 e(k) + \quad V_6[e(k) - e(k-1) + e(k-2)] \qquad \text{...(7)}$$

where

the input vector consists of $e(k)$, $e(k-1)$, $e(k-2)$.

o_1 and o_2 are the outputs of the neural networks that can be obtained from non-linear Pollywog wavelet activation functions and has nonlinear relationship as presented in the following function:

$$O_\gamma = (3(net_\gamma)^2 - (net_\gamma)^4)e^{-0.5(net_\gamma)^2} \qquad \text{... (8)}$$

where $\gamma = 1,2$

The control law of the feedback nonlinear neural control current action can be proposed as follows:

$$i(k) = i(k-1) + O_1 W_1 + O_2 W_2 \qquad \text{....(9)}$$

The control parameters $V_1....V_6$ and W_1, W_2 of the nonlinear neural controller are adjusted using slice genetic optimization algorithm.

Learning Slice Genetic Algorithm (Sga)

Genetic algorithms (GAs) were invented by John Holland and were developed by him and his students and colleagues at the University of Michigan in the 1960s and 1970s. Holland's GA is a method for moving from one population of "chromosomes" (e.g., string of ones and zeros, or "bits") to a new population by using a kind of "natural selection" together with genetic inspired operators of crossover, mutation and inversion. Each chromosome consists of "genes" and each gene being an instance of a particular "allele" (e.g., 0 or 1). GAs has three main operators: selection, crossover, and mutation. [11 and 12] .

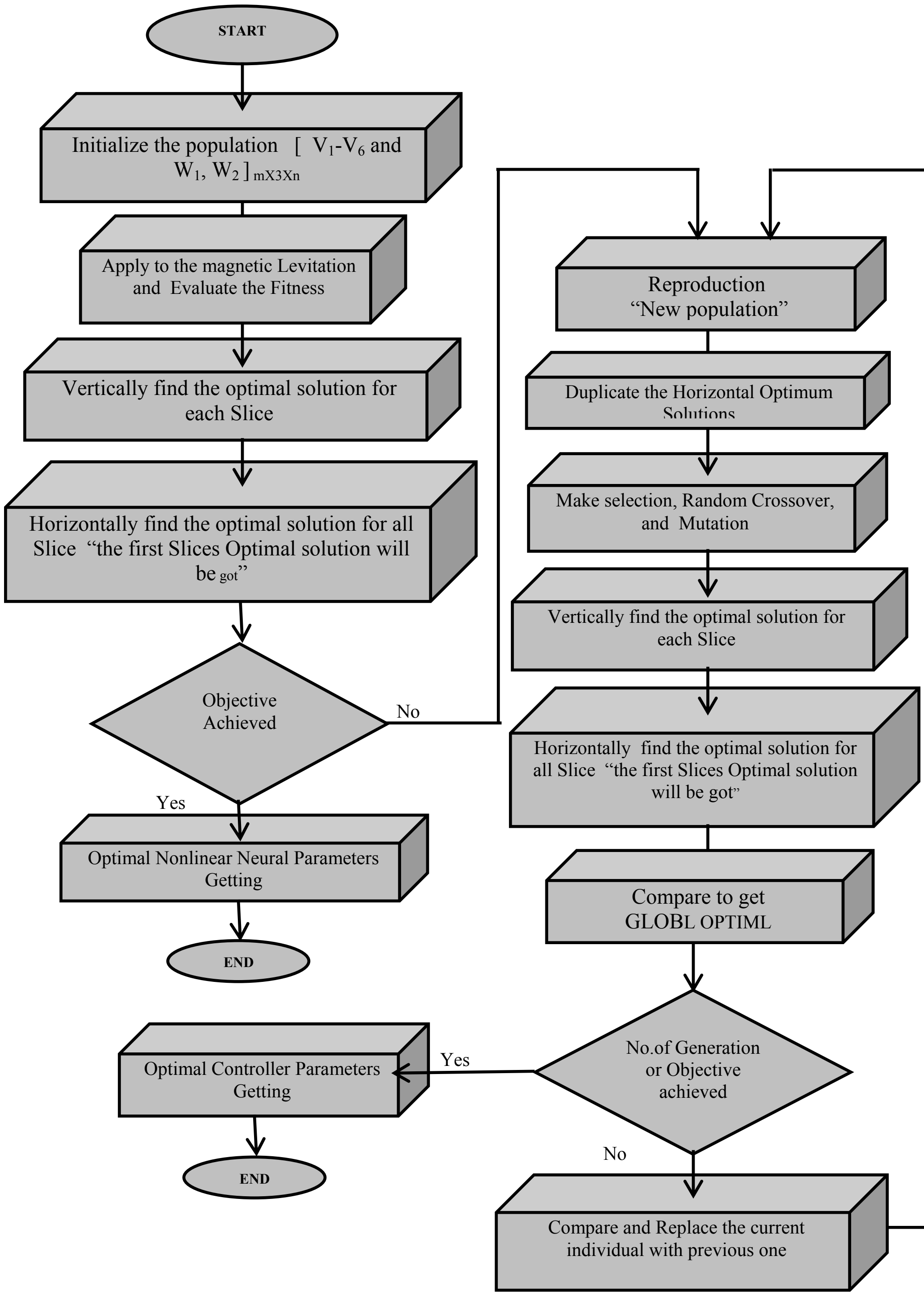
The main advantages of using slice genetic algorithm are to improve the convergence capability of the search, increasing the accuracy, reducing processing time and finally improving the tracking error of the magnetic levitation system.

Given a clearly defined problem to be solved using the slice genetic algorithms for candidate solutions for the nonlinear neural controller can be described as follows [11 and 12]:

a) Start with a randomly n slice generated population.
b) Compute the fitness for each chromosome in each slice.
c) Vertically for each slice in the population compute the global maximum fitness.
d) Horizontally in the population compute the slices global maximum fitness.
e) Search and find the duplicated chromosome horizontally which sponsor with horizontal maximum fitness.
f) Select a pair of parent chromosomes from the current population
g) Crossover the pair at a randomly chosen point to form two offspring.
h) Mutate the two offspring at each locus with probability (the mutation probability or mutation rate), and place the resulting chromosomes in the new population.
i)Compute the fitness value to the vertically find the slices global maximum fitness.
j)Horizontally find the slice global maximum fitness "i.e. maximum fitness in the same position".
k) Find the optimal global by comparing step h to step d.
l)Replace the current population with new population.
m) Repeat Step e to l until stopping criterion or the maximum number of generation is achieved**.**

Figure 5 shows the general flowchart for the slice genetic algorithm: In this work, it is satisfactory to take four slices thus; dimensions of each slice can be calculated as equation (10).

$$Dim[n \times m] = \left[\frac{(\text{Max. Population Size})}{\text{No. Slices}} \times \text{No. Weights} \right] \qquad \text{... (10)}$$



Figure(5). The slice genetic algorithm flow diagram.

The (MSE) mean square error function, as in equation (11) is a criterion for estimating the performance of the ball position tracking error.

$$J = \frac{1}{N}\sum_{k=1}^{N}(Desired_{position} - Actual_{position})^2 \qquad \ldots(11)$$

Since the SGA maximizes its fitness function, it is necessary to map the objective function (MSE) to the fitness function by using equation (12) [13].

$$Fitness() = \frac{1}{Objective() + \mu} \qquad \ldots(12)$$

where
the μ is a constant > 0 chosen to avoid division by zero.
The main core of the slice genetic algorithm is dividing the population into slices, in which the optimization problem is implemented in multi dimensions search space. Therefore, increasing the speed of search, find close optimal solution and reducing the number of function evaluation [11 and 12].

Simulation Results

Table 1 shows the parameter values of the magnetic levitation model [5].
The nonlinear dynamic behavior of the magnetic ball levitation system has been demonstrated in Fig 6. In this figure, the ball positioned reaction is fast and unstable when an open loop step response is applied. To tackle this problem and to increase the stability of the whole dynamic behavior of the system, a nonlinear neural controller has been used to prevent the steel ball to fall or attach itself to the electromagnetic system.

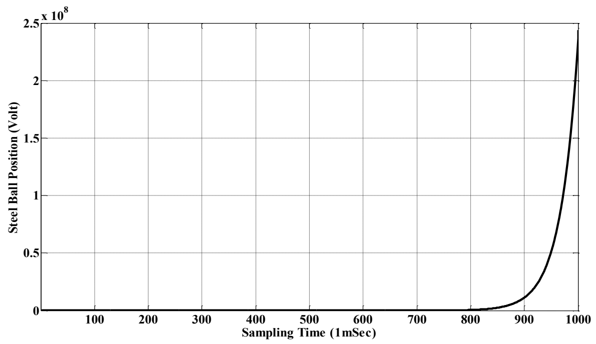


Figure.(6). Open loop magnetic levitation response.

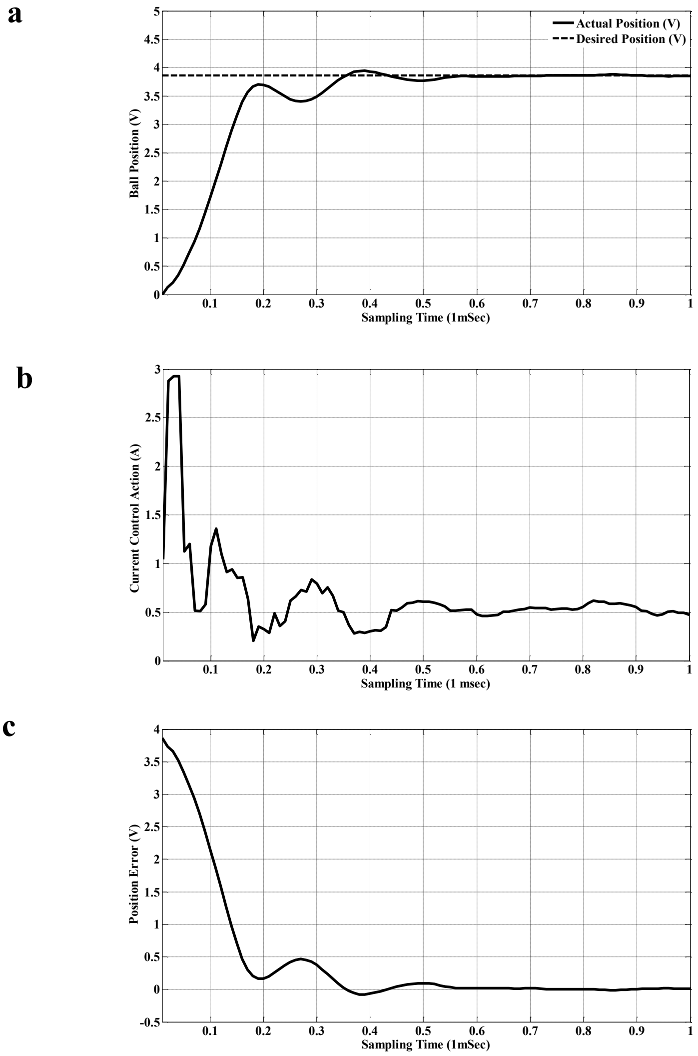
The first stage of operation is to set the following parameters of the SG algorithm which consists of 4 slices each slice has dimension (12×8) .with maximum population size is equal to 48 and the population size for each slice is equal to 12 and the number of weight in each slice is 8 because there are eight parameters of nonlinear neural controller and the number of iteration is equal to 20.
From simulation result, Fig. 7a shows the response of the closed loop time response of the ball position output of the magnetic levitation system to change a step where the measured ball distance of the magnetic levitation system represents the voltage across the Hall effect sensor can be expressed as [5 and 9]:

$$d = \beta\frac{1}{y^2} + \gamma \times i + \alpha + w \qquad \ldots(13)$$

Where

β is equal to 4.25×10^{-4} V.m^2; γ is equal to 0.31 V/A;
α is equal to 2.48 V

Therefore, the time response specification of the ball position output of the magnetic levitation system as follows: 0.187 mSec rising time; 0.563 mSec settling time and 0.18 volt overshoot at transient state at 0.85 mSec then at steady-state the error is approached to zero value at 0.562 mSec when the desired position is 3.866 volt and the external disturbance effect is very small during 1000 samples.



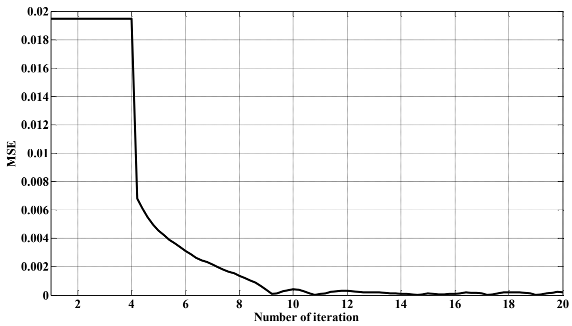
Figure(7). Simulation results (a) position output for magnetic levitation system; (b) control action; (c) position error.

The robust nonlinear neural current control action response is shown in Fig. 7b that it has maximum value 2.87 Amp. at transient state in order to keep the position output of the steel ball of the magnetic levitation system within desired point 2 cm or 3.866 volt and minimize tracking position error of the system and reduce the disturbance and noise effect on the system which has been added to investigate the robustness and adaptation of the control tuning methodology and to evaluate the performance rejection of the model uncertainties. The error between the desired ball position and the magnetic levitation system position output shows in Fig. 7c where the maximum error is 0.18 volt at the transient state response while at steady-state; the error is approximated to zero value with very small oscillation due to the effect of disturbance and noise signal. Table 2 shows the optimal parameters for the neural controllers that have been tuned based on slice genetic algorithm.

Table (2). The parameters of the nonlinear neural controller.

V_1	V_2	V_3	V_4	V_5	V_6	W_1	W_2
0.95	-0.58	0.12	0.62	0.73	0.82	0.91	0.42

Mean square error (MSE) is used as the performance index in the control tuning methodology and it is clear by showing the convergence of the position tracking error for the ball position magnetic levitation system at 20 iterations, as shown in Fig. 8.



Figure(8). The performance index

CONCLUSIONS

The results of the Matlab simulation of the proposed control off-line tuning algorithm for the nonlinear neural controller for the single axis magnetic levitation system based on slice genetic algorithm which has been presented in this paper show the following properties:

- The off-line tuning neural control parameters are fast and optimal stable in terms of the number of fitness evaluation which has minimized based on a powerful tuning slice genetic algorithm.
- The capability for reducing the tracking errors to zero approximation because the suitable current control action value which has smoothness and optimum generation.
- The controller robustness performance of the position tracking has verified through adding the noise/disturbance signals to the system.

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