Genetic Algorithm Based PID Controller Design for a Precise Tracking of Two-Axis Piezoelectric Micropositioning Stage

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Abstract

In this paper, an intelligent tracking control system of both single- and double-axis Piezoelectric Micropositioner stage is designed using Genetic Algorithms (GAs) method for the optimal Proportional-Integral-Derivative (PID) controller tuning parameters. The (GA)-based PID control design approach is a methodology to tune a (PID) controller in an optimal control sense with respect to specified objective function. By using the (GA)-based PID control approach, the high-performance trajectory tracking responses of the Piezoelectric Micropositioner stage can be obtained. The (GA) code was built and the simulation results were obtained using MATLAB environment. The Piezoelectric Micropositioner simulation model with the (GA)-based PID control is illustrated to show the validity of the proposed control method for practical applications, such as scanning microscopy.

1. Introduction

In recent years, piezo-actuators have been widely used in high-precision positioning applications due to their special properties of: (i) nanometer and micrometer scale resolution; (ii) a high stiffness; and (iii) a fast response. However, since almost all the materials in the piezo-actuators are ferroelectric, their responses to applied electric fields exhibits fundamental hysteresis behavior. This always leads to the severe inaccuracies and instabilities when the piezo-actuator is operated in an open-loop fashion [1]. Moreover, the hysteresis characteristics of piezo-actuators are usually unknown and it is difficult to establish a dynamic model for systems with a hysteresis effect. These cause increased difficulties in using piezo-actuated motion systems in positioning control situations with high performance requirements [2, 3].

Many Researchers deal with the problem of precise tracking control of a piezoelectric actuators and micropositioner stages. In 2004, Shieh et al, [1] proposed an adaptive backstepping displacement tracking control for piezoelectric actuating mechanism. The trajectory tracking of a large-displacement piezoelectric actuator (LDPA) using a nonlinear observer-based variable structure control (VSC) was developed by Hwang; et.al. In 2005 [4].

The intelligent control systems are employed also to implement a precise tracking for the micropositioner stage. In 2006, Lin et al. [5] who proposed an adaptive wavelet neural network (AWNN) control with hysteresis estimation to control performance of a piezo-positioning mechanism. In the field of optimal control, Shieh in 2008 [6] utilize the optimal LQR control approach to tune a PID controller to control a micropositioner stages position in an effective way.

This paper endeavors to design a control system using Genetic Algorithm to accurately control a piezoelectric micropositioner. Genetic Algorithm or in short GA is a stochastic algorithm based on principles of natural selection and genetics, in other words, it is a stochastic global search method that mimics the process of natural evolution. Using genetic algorithms to perform the tuning of the controller will result in the

optimum controller being evaluated for the system every time [7]. Genetic algorithms (GAs) were invented by John Holland in the 1960s and were developed by Holland and his students and colleagues at the University of Michigan in the 1960s and the 1970s. In contrast with evolution strategies and evolutionary programming, Holland's original goal was not to design algorithms to solve specific problems, but rather to formally study the phenomenon of adaptation as it occurs in nature and to develop ways in which the mechanisms of natural adaptation might be imported into computer systems. Holland's 1975 book Adaptation in Natural and Artificial Systems presented the genetic algorithm as an abstraction of biological evolution and gave a theoretical framework for adaptation under the GA. Holland's GA is a method for moving from one population of "chromosomes" (e.g., strings of ones and zeros, or "bits") to a new population by using a kind of "natural selection" together with the genetics−inspired operators of crossover, mutation, and inversion. Each chromosome consists of "genes" (e.g., bits); each gene is an instance of a particular "allele" (e.g., 0 or 1) [8]. It is worth mentioning, that the (GAs) start with no knowledge of the correct solution and depends entirely on responses from their environment and evolution operators such as reproduction, crossover, and mutation to arrive to the best solution. By starting at several independent points and searching in parallel, the algorithm avoids local minima and converging to suboptimal solutions [9].
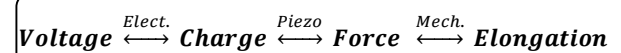
The paper is outlined in the following way: Sec. 2 explains the physical background of the piezoelectric actuators in general. Sec. 3 gives the necessary description of the piezoelectric micropositioner device. Sec. 4 gives the modeling of the piezoelectric micropositioner. The genetic algorithm is explained in sec. 5 while the tuning of PID using genetic algorithm is illustrated in sec. 6. The simulation results and the analysis of the results are given in sec. 7. Finally the conclusion is presented in sec. 8.

2. Physical Background of Piezoelectric Actuators

The piezoelectric actuator (PEA) is a well-known commercially available device for managing extremely small displacements in the range of 10 pm (pm=10^{-12} m) to 100 μm. The ratio of the input voltage and the output elongation is very satisfactory for this purpose. A disadvantage, however, is its highly nonlinear input/output behavior. More specifically, a PEA shows hysteresis behavior. In simple terms, this means that for a certain input, there is no unique output. Instead, the output depends on the input history. For high-accuracy positioning and tracking systems, the piezo-actuated positioning mechanism should be equipped with a controller. Modern controller design is based on a model of the system to be controlled. For piezo-actuated positioning mechanisms, the dynamical aspects of the PEA play a dominant role [10].

Dielectric materials are insulators, thus, there is an electrical relation between electrical voltage and electrical charge. Piezoelectric is a special type of dielectric in the sense that, in piezoelectric materials, an externally applied force induces an electrical charge. Conversely, an applied electrical charge induces a force [10]. The former effect is known as the piezoelectric effect and was discovered in 1880 by the Curie brothers. The latter effect is the inverse piezoelectric effect. Both pressure electricity and piezoelectricity were used to describe the same phenomenon. Besides the piezoelectric and inverse piezoelectric effect, there are already mentioned electrical relation between voltage and charge, and a mechanical relation between force and elongation [11].

$$\textit{Voltage} \xleftrightarrow{\textit{Elect.}} \textit{Charge} \xleftrightarrow{\textit{Piezo}} \textit{Force} \xleftrightarrow{\textit{Mech.}} \textit{Elongation}$$

Fig. 1. Schematic Representation of the Different Relations in a PEA.

In Fig. (1), a schematic representation of the different relations is given. The piezo effect is the connection between the electrical and mechanical domains. Due to this effect, piezoelectric are potentially useful as electromechanical actuators. In naturally occurring piezoelectric materials, such as quartz, the (inverse) piezoelectric effect is too small to be of practical use. Fabricated piezoelectric polycrystalline ceramics are much more suitable for actuator purposes because the proper mixture of ingredients can influence the useful properties, such as maximum elongation. A disadvantage of fabricated piezoelectric ceramics is that a hysteresis effect is encountered between electrical voltage and electrical charge [11]. Historical perspectives of the piezoelectric effect as well as recent advances in ceramic and thin film actuators are provided in [12, 13], and [14].

3. Description of The Piezoelectric Micropositioner

The double-axis micropositioner driven by stacked piezo-actuators used in this study is a micropositioner with displacement range of ($0 - 80\,\mu m$) in the *x* and *y* directions. The outline sketch of this stage is shown in Fig. (2-a), and it contains the following elements: Stacked piezo-actuator, heavy base, flexure mount, lever arm, movable top plate, and Strain-gauge transducers. Its single-axis motion working principle can be shown in Fig. (2-b). The main body of the stage is fixed to a heavy base and the movable plate on the top of the stage is a platform for the components mounted to be scanned. The movement of the top plate is due to an internal lever-transmission of extension of the built-in stacked piezo-actuators with solid state flexure hinges. When an input voltage is applied to the stage, the extension of the stacked piezo-actuators occurs and then this extension causes the bending of the flexure mounts. This bending gives rise to a deviation of the top plate [15].
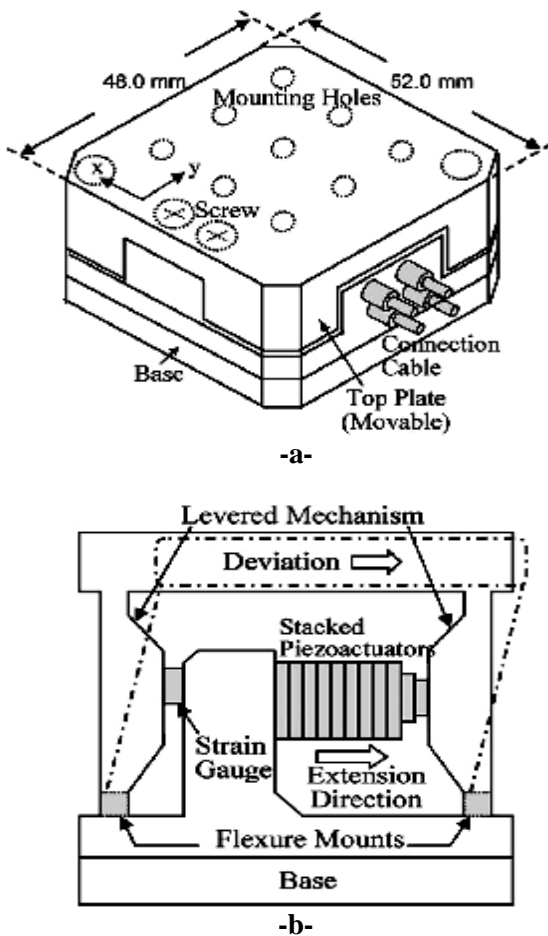

-a-

-b-

Fig. 2. a- Outline Sketch. b- Working Principle of the Piezo-Positioning Stage.

A block diagram for a control system setup of the piezoelectric micropositioner is shown in Fig. (3), which contains has a voltage amplifier, signal conditioner, and computer with data acquisition interface.
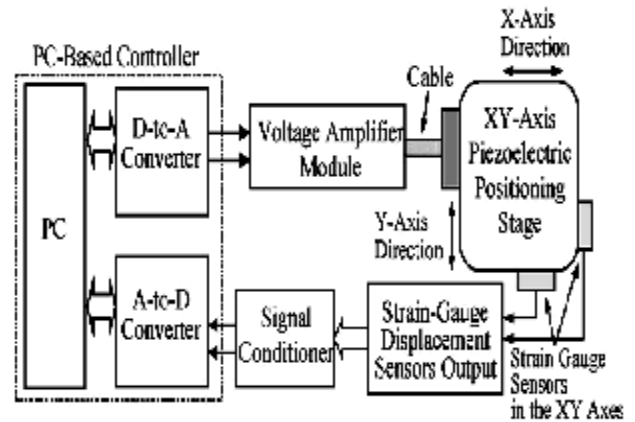

Fig. 3. A Block Diagram for a Control System Setup of the Piezoelectric Micropositioner.

In Fig. (3), the equipped devices are briefly described as follows [6]:

i. Voltage amplifier was developed by high voltage – type Op-Amplifier with model PA240, manufactured by APEX Microtechnology, USA, which has the specification of maximum peak-peak voltage 350V, maximum output current of 250 *mA*, and bandwidth of 3MHZ. Moreover, the linear amplification gain of 5 is set. The amplifier implementation for driving the piezoelectric micropostioner is shown in Fig. (4), in which a phase lead-lag compensator is cascaded to obtain an improved stability in the sense of bode diagram.

ii. Signal conditioner for strain gauge transducer was set up by chip with model 1B32, produced by (Analog Devices, Inc.). The output voltage range was set to (0 -10) V for the ranged displacement of ($0-80\mu\text{m}$).

iii. A computer for control algorithm implementation and a data acquisition board with analog to digital (A/D) and digital to analog (D/A) conversion were applied.
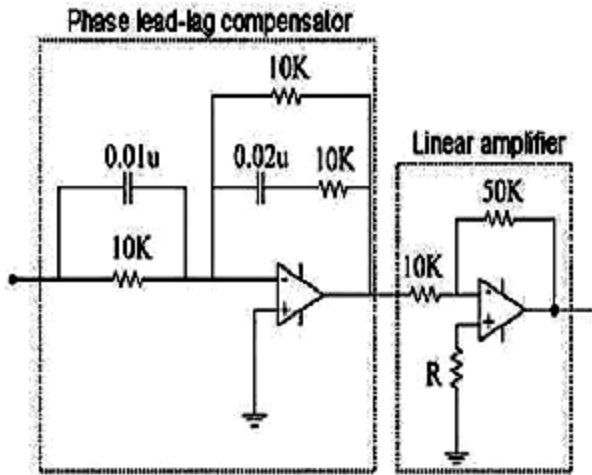
Fig. 4. Diagram of the Drive Amplifier Circuit for the Piezoelectric Micropositioner.

To show the usability of the driving amplifier and strain gauge signal conditioner, a triangular displacement-trajectory response from the Piezoelectric Micropostioner without control approach implementation is shown in Fig. (5) [6]. It appears from Fig. (5) that the established control system in this study consists of the Piezoelectric Micropositioner, driving amplifier, strain-gauge signal conditioner is applicable for controller development.
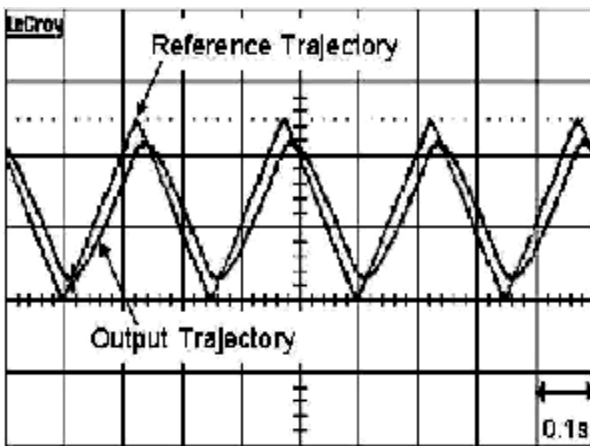

Fig. 5. Output Displacement Response from the Open-Loop Piezoelectric Micropositioner.

4. Modeling of Piezoelectric Micropositioner System

For suitability of controller development, a Dynamic model of the piezoelectric micropositioner which is a second order linear transfer function model is considered in this study. Originally this model is identified by using

a dynamic signal analyzer that is used to capture the magnitude response in frequency domain. Then, a curve fitting tool in MATLAB computer software is adopted to find out an approximated second-order linear transfer function whose magnitude response in frequency domain is very close to the actual one captured by the dynamic signal analyzer. The second-order linear transfer function determined by the curve fitting method is given as follows [6]:

$$\frac{Y(s)}{U(s)} = \frac{30695.04}{s^2+350.48s+30695.04} \qquad \ldots(1)$$

Where:
$Y(s)$: denotes the output displacement.
$U(s)$: denotes the input voltage.

To confirm the accuracy of the identified mathematic model (Eq. (1)), the magnitude responses in frequency domain of the actual system and the mathematic model are shown in Fig. (6). From Fig (6), it appears that the identified mathematic model approaches the actual one. In other words, the identified model can be adopted for controller development in a ranged frequency domain [6].
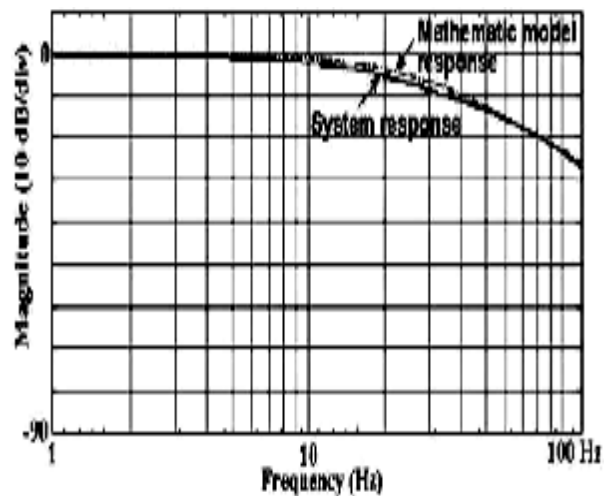

Fig. 6. Magnitude Response in Frequency Domain from the Piezoelectric Micropositioner and the Identified Model.

Furthermore, a displacement time-response of both the practical system and identified model to a triangular trajectory is shown in Fig. (7) to validate the mathematic model of (Eq. (1)).
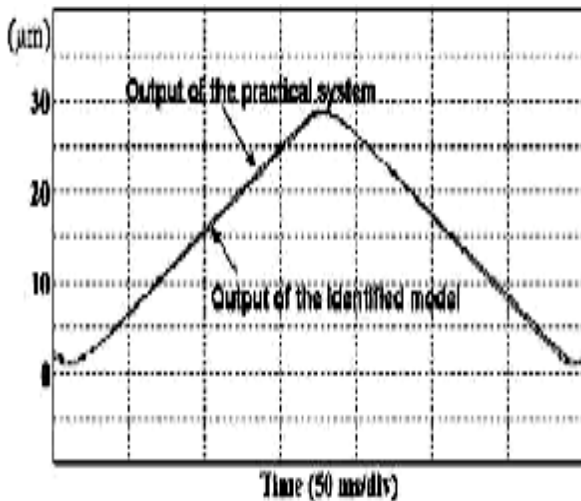
Fig. 7. A Displacement Time-Response of Both the Practical System and Identified Model to a Triangular Trajectory [6].

According to (Eq. (1)), the following states are defined:

$$x_1 = y, \; and \qquad x_2 = \dot{y} \qquad\qquad …(2)$$

Where:

x_1: denotes the displacement.

x_2: denotes its velocity.

With the assumption of Eq. (2), the linear state equation corresponding to (Eq. (1)) can be expressed by:

$$\dot{x} = Ax + Bu$$

$$y = Cx \qquad\qquad …(3)$$

Where:

$$A = \begin{bmatrix} 0 & 1 \\ -a_2 & -a_1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -30695.04 & -350.48 \end{bmatrix},$$

$$B = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 30695.04 \end{bmatrix}.$$

And,

$$C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

Before we designing a GA based PID controller for the piezoelectric micropositionor stage system (Eq. (1)), the system should be tested for controllability properties. In order to test system controllability, the controllability matrix is first calculated as follows:

$$S = [B \; AB] \qquad\qquad …(4)$$

Where:

S: Controllability matrix.

A, and **B** are the piezoelectric micropositioner stage system state space matrices.

Substituting the above state space matrices into Eq.(4) above yield:

$$S = \begin{bmatrix} 0 & 30695 \\ -30695.04 & -1.0758 \times 10^7 \end{bmatrix} \qquad …(5)$$

The rank of the above controllability matrix is found to be 2, which means that the system is fully controllable.

5. Genetic Algorithm

Genetic algorithm is a powerful search algorithm that performs an exploration of the search space that evolves in analogy to the evolution in nature [16]. (GAs) use probabilistic transition rules instead of deterministic rules, and handle a population of potential solutions known as individuals or chromosomes that evolve iteratively. Each iteration of the algorithm is termed as a generation. The evolution of solutions is simulated through a fitness function and genetic operators such as reproduction, crossover and mutation. The fittest individual will survive generation after generation, and will also reprodue and generate offsprings that might be stronger. At the same time, the weakest individuals disappear from each generation [17]. A genetic algorithm (Fig. (8)) is typically initialized with a random population. This population (mating pool) is usually represented by a real-valued number or a binary string called a chromosome. How well an individual performs a task is measured and assessed by the objective function, which assigns each individual a corresponding number called its fitness. The fitness of each chromosome is assessed and a survival of the fittest strategy is applied [18]. There are three main operators for a genetic algorithm – reproduction, crossover and mutation.
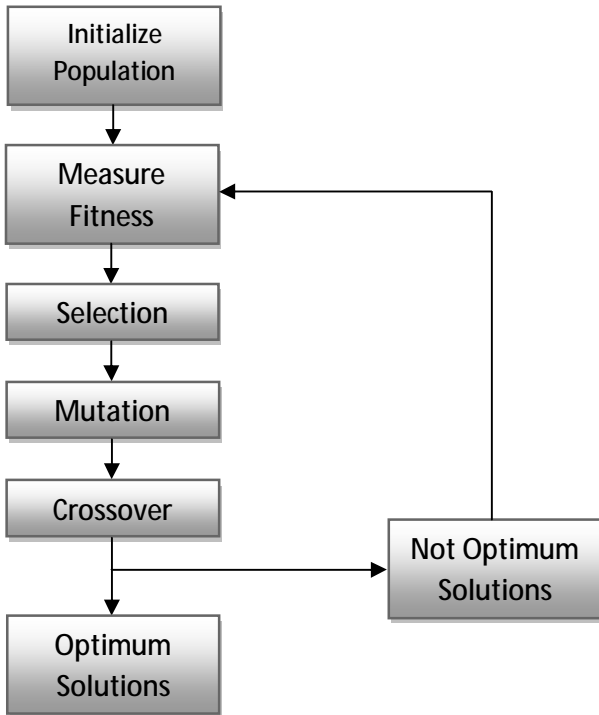
5.2. Crossover

Once the selection process is complete, the crossover algorithm is initiated. The crossover operations swap certain parts of the two selected strings in a bid to capture the good parts of old chromosomes and create better new ones. Genetic operators manipulate the characters of a chromosome directly, using the assumption that certain individual's gene codes, on average, produce fitter individuals. The crossover probability indicates how often crossover is performed. A probability of 0% means that the 'offspring' will be exact replicas of their 'parents' and a probability of 100% means that each generation will be composed of entirely new offspring. The simplest crossover technique is the Single Point Crossover [9,18].

5.3. Mutation

Using selection and crossover on their own will generate a large amount of different strings. However there are two main problems with this:

1. Depending on the initial population chosen, there may not be enough diversity in the initial strings to ensure the GA searches the entire problem space.
2. The GA may converge on sub-optimum strings due to a bad choice of initial population. These problems may be overcome by the introduction of a mutation operator into the GA. Mutation is the occasional random alteration of a value of a string position. It is considered a background operator in the genetic algorithm. The probability of mutation is normally low because a high mutation rate would destroy fit strings and degenerate the genetic algorithm into a random search. Mutation probability values of around 0.1% or 0.01% are common. These values represent the probability that a certain string will be selected for mutation i.e. for a probability of 0.1%. One string in one thousand will be selected for mutation [9, 18].

6. GA Based Tuning of The Controller

The optimal value of the PID controller parameters K_p, K_i, K_d are to be found using GA. All possible sets of controller parameter values are particles whose values are adjusted to minimize the objective function, which in this case is the error criterion, and it is discussed in detail. For the PID controller design, the

Fig. 8. Flowchart of GA Programming.

5.1. Reproduction

During the reproduction phase the fitness value of each chromosome is assessed. This value is used in the selection process to provide bias towards fitter individuals. Just like in natural evolution, a fit chromosome has a higher probability of being selected for reproduction [9]. An example of a common selection technique is the 'Roulette Wheel' selection method;see Fig. (9). Each individual in the population is allocated a section of a roulette wheel; the size of the section is proportional to the fitness of the individual. A pointer is spun and the individual to whom it points is selected. This continues until the selection criterion has been is met [19].
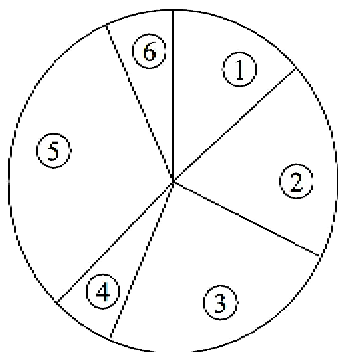

Fig. 9. Depiction of Roulette Wheel Selection.

controller settings estimated results in a stable closed loop system are ensured.

6.1. Objective Function for the GA

The objective functions considered are based on the error criterion. A number of such criteria are available. In this paper controller's performance is evaluated in terms of integral time absolute error criteria (ITAE). The error criterion is given as a measure of performance index given by the equation for the integral of time multiplied by absolute error (ITAE) [18]:

$$I_{ITAE} = \int_0^T t|e(t)|dt \qquad \qquad …(6)$$

Where:
T: Final time of simulation.

7. Implementation of GA Based PID Controller

To ensure optimal control performance at nominal operating conditions, GA can be applied to the tuning of PID controller gains (where this GA is programmed using m-file [MATLAB File] code). The block diagram (Fig. (10)) for the entire system is given below and also the genetic algorithm parameters chosen for the tuning purpose are shown in Table (1).

Table 1,
Parameters of GA.

GA Property	Value / Method		
Population Size	10		
Maximum Number of Generations	10		
The Range of Tuning Parameters	K_P	K_I	K_d
	4-4.5	221-230	0.008-0.0085
Performance Index/Fitness Function	ITAE		
Selection Method	Roulette Wheel		
Crossover Method	Arithmetic Crossover		
Crossover Probability	0.8		
Mutation Method	Uniform		
Mutation Probability	0.05		
Termination Condition for GA	Maximum Number of Generation is Achieved **or** The Value of Fitness is Fixed for Next Generations		

7.1. Simulation and Analysis of Results

After giving the above parameters to GA, the PID controllers can be easily tuned, the proper optimized gain values of controller are obtained with the implementation of GA based PID controller given in Table (2) .

Table 2,
GA Based PID Controller Gain Values.

Gain Parameters	K_p	K_i	K_d
Values	4.04877	222.27698	0.0084

To show the performance of the control system, simulation time responses from the piezoelectric micropositioner with the proposed genetic PID controller are carried out with MATLAB-SIMULINK (R2009a) package.

7.1.1. Single-Axis Simulation Results

The single-axis (either x or y direction) piezoelectric micropositioner stage is simulated using the gain parameter values taken from Table (2) with the following desired test signals:

Test Signal1: step function with magnitude=**1** μm
Test Signal2: sinusoidal function = **Asin(10t)**, where the amplitude **A** is **1** μm.
Test Signal3: square function with amplitude equal to **1** μm and frequency equal to 10 ras/sec.

The simulation results of the single-axis piezoelectric micropositioner stage are shown in Fig. (11-a) for the Test Signal1, while the control action is shown in Fig. (11-b). It can be noticed that the system succeed to reach to its desired position in less than (0.015 sec) with a smooth behavior.

For further confirmation, the validity of the control system in many practical applications, the time responses to commanded sinusoidal and square trajectories (Test Signal 2 & 3) with amplitude **1** μm are obtained. For the Test Signal2, the simulation results of the single-axis piezoelectric micropositioner stage are shown in Fig. (12-a). It is very clear that the proposed genetic PID controller is able to track the desired sinusoidal reference efficiently. The control action is shown in Fig. (12.b). For the Test Signal 3 it is noticed in Fig. (13-a) that the PID based GA controller is also able to track the reference signal also with efficient manner. The control action for

the PID based GA controller under Test Signal 3 can be seen in Fig. (13-b).

7.1.2. Double-Axis Simulation Results

In order to obtain a circle-shaped trajectory for the double-axis piezoelectric micropositioner stage, the following desired references for both x- and y-axis are chosen to be:

$$x - \text{axis ref} = A \sin(10t),$$

$$y - \text{axis ref} = A \sin\left(10t + \frac{\pi}{2}\right) \qquad \ldots(7)$$

Where $A = 1\,\mu m$ the time response of the commanded x- and y-axis stages are shown in Fig. (14-a) and Fig. (14-b), while the control actions of both x- and y-axis stages are illustrated in Fig. (14-c). The efficient tracking of both stages to the desired references is an evident to the potential of the designed optimal PID based GA controller. The circular-shaped trajectory is shown in Fig. (15), where the piezoelectric micropositioner is able to track a circle trajectory with $1\,\mu m$ radius.
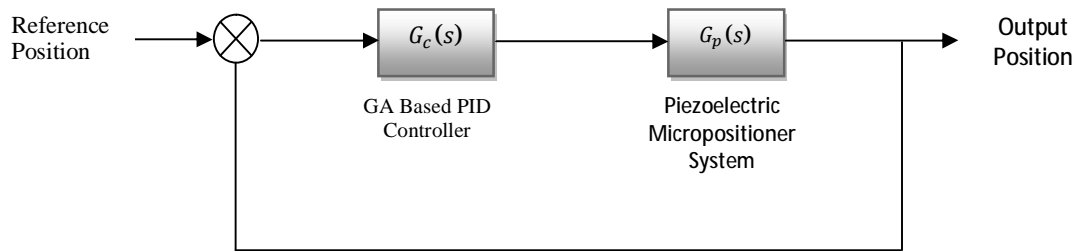
Fig. 10. Block Diagram of the Entire Piezoelectric Micropositioner System.
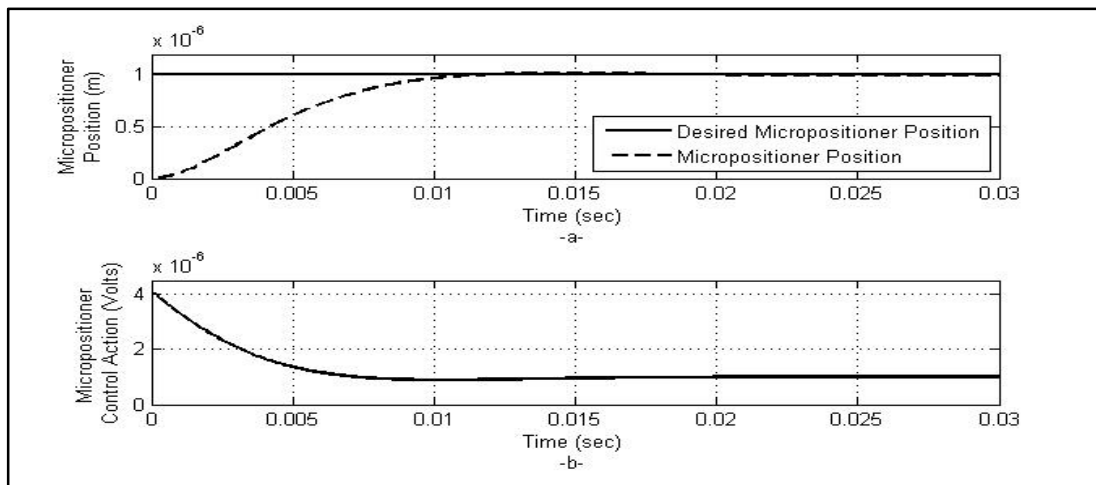
Fig. 11. Simulation Results with Test Signal 1 of Single-Axis Piezoelectric Micropositioner Stage Position. a- TimeResponse. b- Control Action.
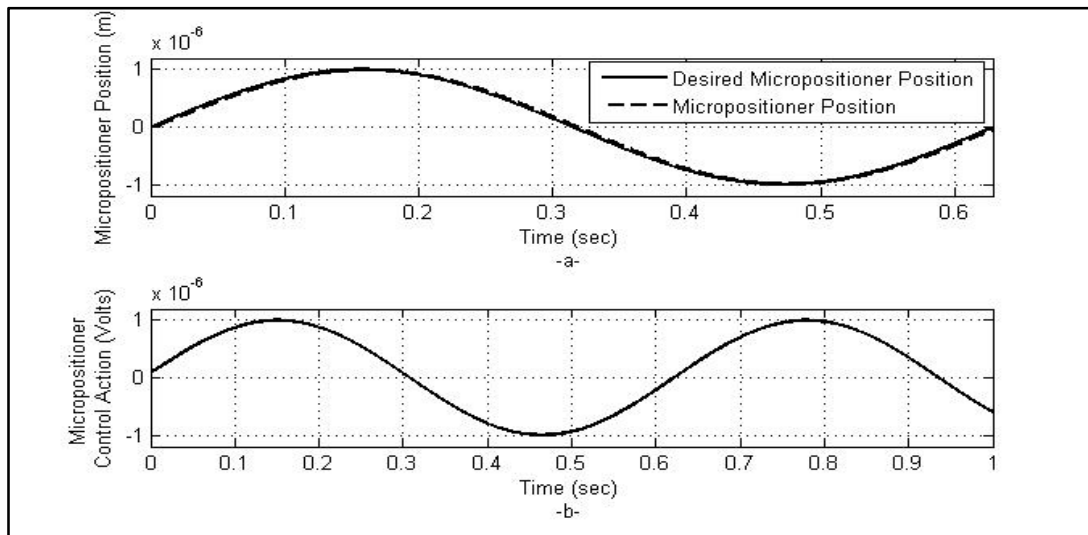
Fig. 12. Simulation Results with Test Signal 2 of Single-Axis Piezoelectric Micropositioner Stage Position.
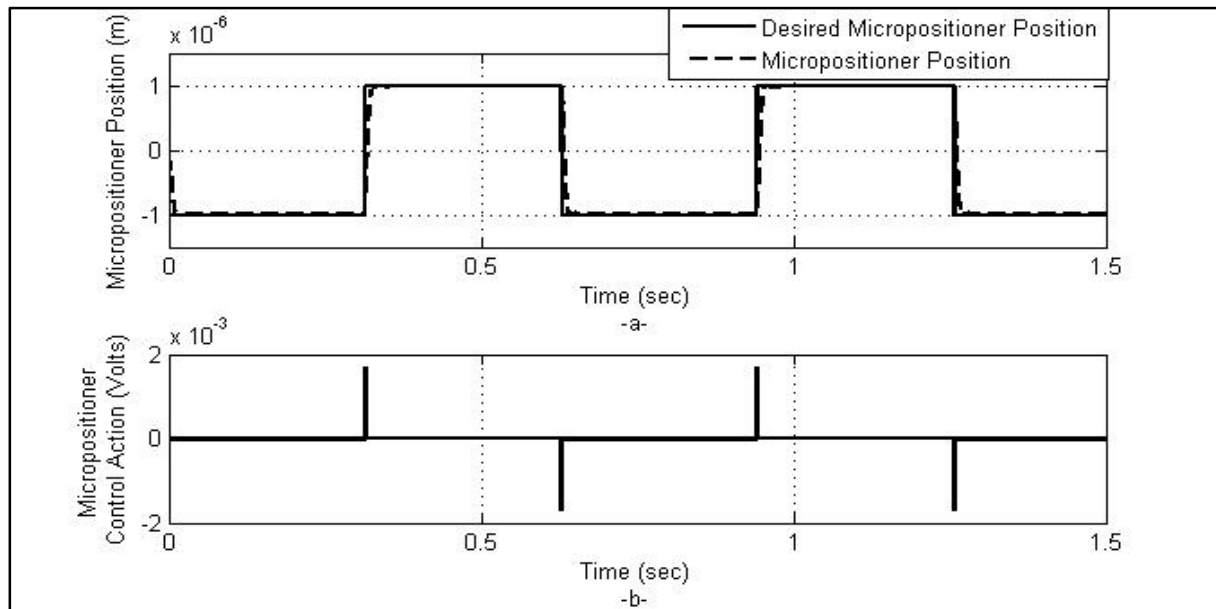**a- Time Response. b- Control Action.**

Fig. 13. Simulation Results with Test Signal 3 of Single-Axis Piezoelectric Micropositioner Stage Position.
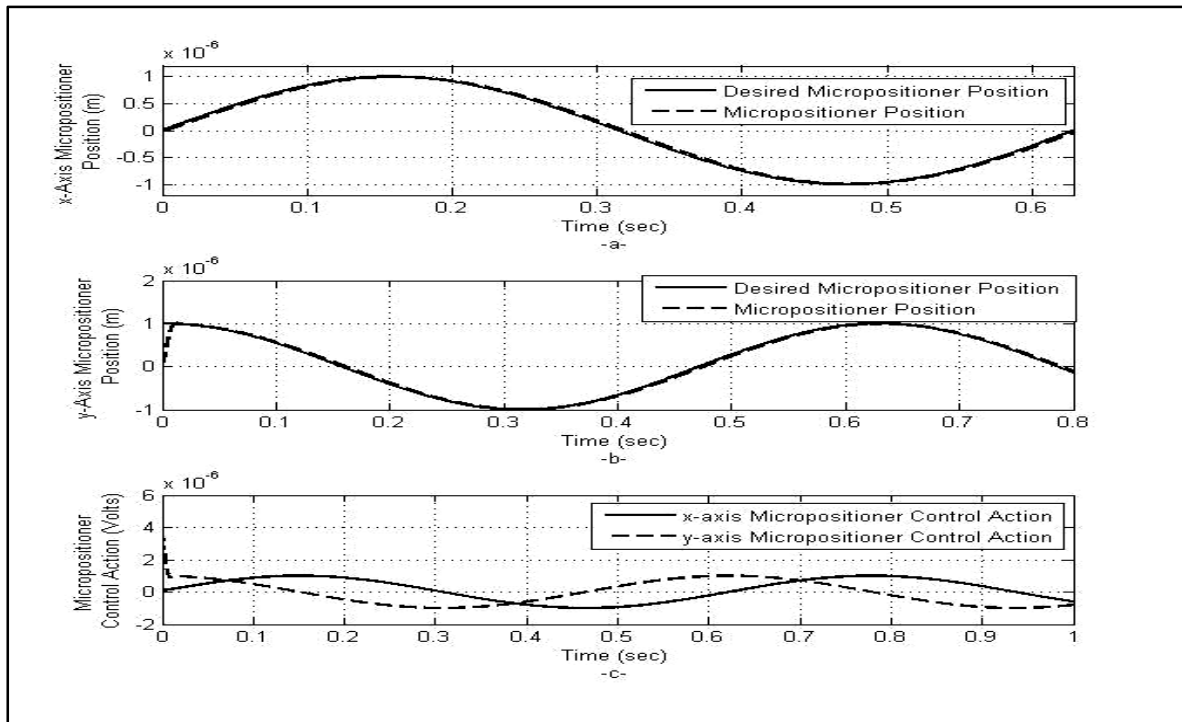**a- Time Response. b- Control Action.**

Fig. 14. Simulation Results with Sinusoidal Ref. Inputs of Double-Axis Piezoelectric Micropositioner Stage Position. a- Time Response of x-Axis. b- Time Response of y-Axis. c- Double-Axis Control Action.
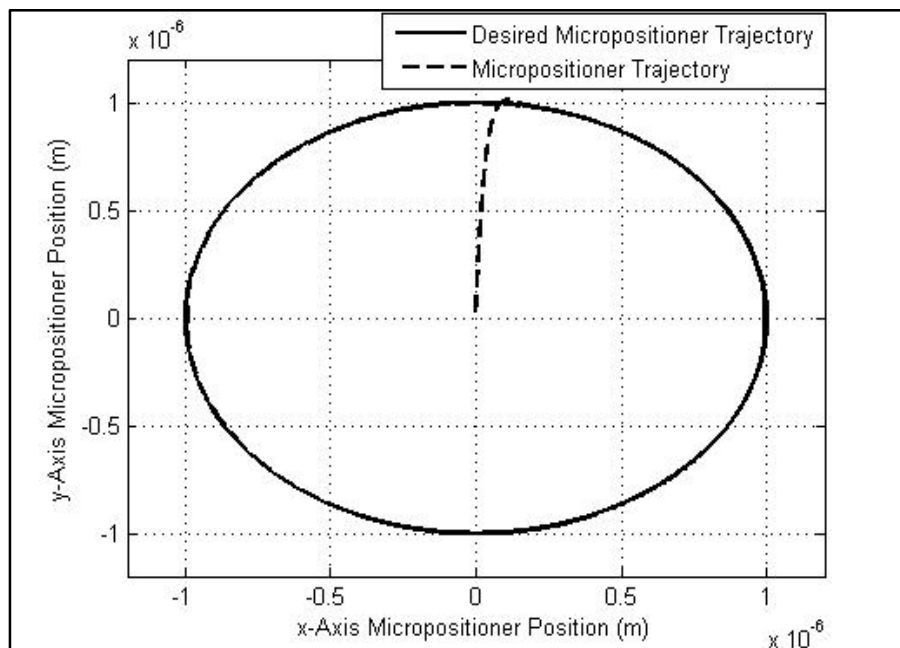

Fig. 15.Simulation Results of Piezoelectric Micropositioner Stage Circle Trajectory.

8. Conclusions

This paper is dedicated to design a control system of a piezoelectric micropositioner, where the control system was developed with the GA PID controller. The GA is used to optimally select the best PID parameters as shown in Table (2), consequently the system response is enhanced, which verify the efficiency of GA as suitable optimization method.

To design the GA PID, an approximated linear second-order transfer function is used. To confirm the validity of the proposed control approach, a simulation program created by using MATLAB package for piezoelectric micropositioner with GA PID was carried out. Finally, the simulation results illustrated the validity of the proposed control system for practical applications in single-axis trajectory tracking and double-axis scanning. This shows that the proposed control approach is perfectly applicable to scanning application.

Notations

$Y(s)$:	Output displacement.
$U(s)$:	Input voltage.
x_1:	Displacement state Variable.
x_2:	Velocity state Variable.
A, B	Piezoelectric state space coefficient
C, D	matrices
S:	Controllability matrix.
I_{ITAE}:	Absolute error criteria.
$e(t)$:	Error function.
T:	Final time of simulation.
K_P	Proportional gain.
K_I	Integral gain.
K_d	Derivative gain.

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تصميم مسيطر تناسبي-تكاملي-تفاضلي بالإعتماد على الخوارزميات الجينية لغرض تتبع دقيق لنظام تموضع كهروإجهادي ذو محورين

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الخلاصة

في هذا البحث ، تم تصميم نظام ذكي للتتبع لغرض السيطرة على نظام تموضع كهروإجهادي لمرحلة ذات محور واحد وذات محورين بإستخدام طريقة الخوارزميات الجينية لغرض تنغيم معاملات مسيطر تناسبي - تكاملي- تفاضلي . إن طريقة تصميم المسيطر التناسبي- التكاملي- التفاضلي بالإعتماد على الخوارزمية الجينية هي طريقة لتنغيم المسيطر ضمن سياق السيطرة المثلى بالإعتماد على دالة هدف محددة . بإستعمال هذا النوع من المسيطرات يمكن الحصول على إستجابات لمسار التتبع بمواصفات إداء عالية لنظام التموضع الكهروإجهادي. إن بناء شفرة الخوارزميات الجينية ونتائج المحاكاة التي تم الحصول عليها تم من خلال بيئة MATLAB وكذلك نموذج المحاكاة مع المسيطر التناسبي- التكاملي- التفاضلي المعتمد على الخوارزمية الجينية قد تم توضيحه لغرض إظهار صلاحية طريقة السيطرة المقترحة للتطبيقات العملية مثل المسح المجهري.