Development of a Swing-Tracking Sliding Mode Controller Design for Nonlinear Inverted Pendulum System via Bees-Slice Genetic Algorithm

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ABSTRACT

A new development of a swing-tracking control algorithm for nonlinear inverted pendulum system presents in this paper. Sliding mode control technique is used and guided by Lyapunov stability criterion and tuned by Bees-slice genetic algorithm (BSGA). The main purposes of the proposed nonlinear swing-tracking controller is to find the best force control action for the real inverted pendulum model in order to stabilize the pendulum in the inverted position precisely and quickly. The Bees-slice genetic algorithm (BSGA) is carried out as a stable and robust on-line auto-tune algorithm to find and tune the parameters for the sliding mode controller. Sigmoid function is used as signum function for sliding mode in order to eliminate the chattering effect of the fast switching surface by reducing the amplitude of the function output. MATLAB simulation results and LabVIEW experimental work are confirmed the performance of the proposed tuning swing-tracking control algorithm in terms of the robustness and effectiveness that is overcame the undesirable boundary disturbances, minimized the tracking angle error to zero value and obtained the smooth and best force control action for the pendulum cart, with fast and minimum number of fitness evaluation.

Keywords: Sliding Mode Controller; Bees-Slice Genetic Algorithm; Inverted pendulum.

INTRODUCTION

Nowadays many research and dissertations consider the inverted pendulum system as a main topic of great interest due to their evolutionary application. Various fields such as rocket technology, missile launchers, air planes, ship, mobile robots and human walking use inverted pendulum [1 and 2]. Traditionally, the problems of inverted pendulum control have been addressed by stabilizing point of pendulum in the inverted position for inverted pendulum system, many control algorithm are proposed in the swing-tracking problems, such as back-stepping with sliding mode controller [3], hierarchical sliding mode controller [4], neural network with sliding mode controller [5], fuzzy with sliding mode controllers [6 and 7], adaptive-fuzzy with sliding mod controller [8], second-order sliding mode controller [9], PID with sliding mode controller [10], pole placement with sliding mode controller [11] , etc.

This work, the cores of the motivation are taken from [4, 7, 12 and 13] because the problems in swing-tracking inverted pendulum are still there waiting to be processed in terms of generating best force control action for inverted pendulum cart, tracking the reference position with minimum swing-tracking error and overcoming undesirable disturbances.

In this paper, the contributions can be described as follows:

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- The swing-tracking control law is developed through high analytical derive accuracy that it is based on sliding mode control, Lyapunov criterion stability and Bees-slice genetic algorithm (BSGA) in order to find the best force control action quickly.
- The swing-tracking error of the inverted pendulum is minimized.
- The chattering phenomenon of the sliding mode control is overcomed.
- The adding of undesirable boundary disturbances are reduced by adaptation performance.
- The capability of the on-line auto-tuning swing-tracking control algorithm is confirmed by experimental work.

The organization of the paper as follows: Section 2 includes description of the nonlinear inverted pendulum model. Section 3, involves details on the nonlinear controller derivation based on sliding mode control and the proposed tuning swing-tracking algorithm based Bees-slice genetic algorithm. The simulation and experimental results are explained in section 4 and the main conclusions are described in section 5.

Inverted Pendulum Model

The inverted pendulum model consists of two parts: the first part is a pendulum cart that it is motion on the x-axis by applying a force control action. The second part is a pendulum that is attached to the side of a pendulum cart and it has a capability to swing in x-y plane as shown in Figure (1). The aim of the force is stabilizing the pendulum in the inverted position.

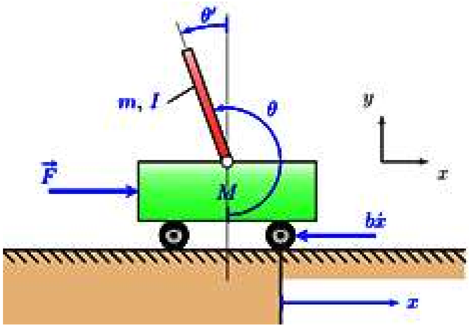


Figure (1): Inverted Pendulum System [14].

The model of the inverted pendulum system can be represented by applying Newton's second law to the linear and angular position, then the equations of motion for nonlinear inverted pendulum system are expressed as follows [1 and 14]:

$$(M+m)\ddot{x}+\beta\dot{x}-mlsin(\theta)\dot{\theta}^2+mlcos(\theta)\ddot{\theta}=F(t) \quad \ldots(1)$$

$$\ddot{x}\cos(\theta)+ml\ddot{\theta}=mgsin(\theta) \quad \ldots(2)$$

The parameter values of the inverted pendulum system are taken from [15] as shown in table 1.

Table 1 the parameter values of the inverted pendulum system [15]

Description	Symbol	Value	Unit
The position of the card.	x	1	m
The angle between the pendulum and its upright position.	θ		rad
The force applied to the cart.	F		N
The mass of pendulum's bob.	m	0.23	kg
The mass of the cart.	M	2.4	kg
The pendulum's length.	l	0.36	M

The friction of the cart.	β	0.1	N/m/sec
The gravitation constant.	g	9.81	m/sec^2

Swing-Tracking Control Design

The most significant thing is to prevent the pendulum drifting from the desired inverted position by finding the control law of the swing-tracking, which is responsible for establishing a smooth force control signal and minimizing the tracking angular error of the pendulum angle. The block diagram of the proposed on-line auto-tuning nonlinear controller structure for the inverted pendulum system is illustrated in Figure (2).

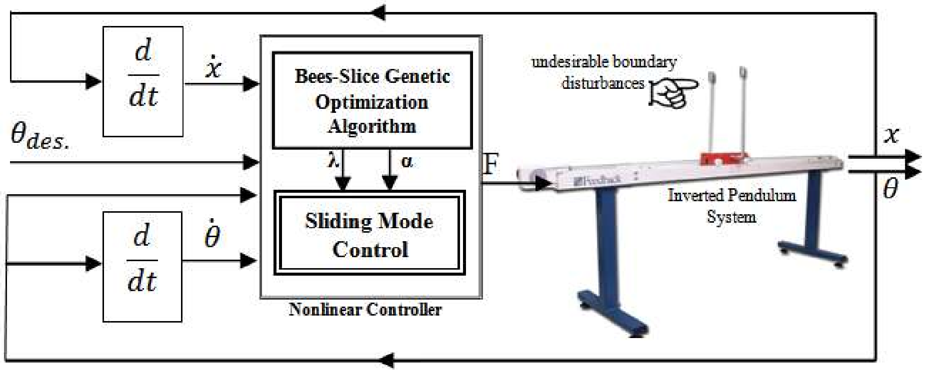


Figure (2): The proposed nonlinear swing-tracking controller structure for inverted pendulum system.

The proposed tuning swing-tracking control algorithm will generate the optimal parameters for an on-line auto- tuning sliding mode controller in order to obtain best and fast force control signal that will minimize the tracking error in the presence of external disturbance and to overcome the chattering effect of the fast switching surface of the sliding mode by reducing the amplitude of the function by using Sigmoid function. The structure of the nonlinear swing-tracking feedback controller consists of two parts:

Part 1#

The nonlinear feedback time-varying control equation based on sliding mode control:
The proposed sliding mode control law based on the sliding surface is defined by Eq. (3) which means, at t→ ∞, the pendulum angle is equal to the desired angle which is equal to zero at inverted position.

$$= \lambda(\theta - \theta_{des}) + \dot{\theta} \qquad \dots(3)$$

Where:
λ: is the positive scalar parameter tuning.
: is the desired angle.
Lyapunov method is used to prove the swing-tracking control law which is global stable at closed loop nonlinear system because it is the simple and successful method represented, thus the constructive Lyapunov equation is described as follows [7 and 9]:

$$- \qquad \dots(4)$$

The time derivative of Lyapunov function in Eq. (4) becomes:

$$\dot{V} \quad \dot{S} \quad S(\lambda\dot{\theta} + \ddot{\theta}) \qquad \dots(5)$$

$$\dot{} \quad (\lambda \dot{} \quad \ddot{\theta}) \quad gn(S) \qquad \dots(6)$$

Where
α : is the positive scalar parameter that guarantees the system trajectory hit the sliding surface at t→ ∞.

$sgn(S)$: is the signum function that can be proposed as a Sigmoid function as equation (7) in order to reduce and overcome the chattering effect of the sliding mode control.

$$gn(S) \quad \alpha(\frac{}{S(\theta)} \quad 1) \qquad \ldots(7)$$

Where

μ: is the positive scalar parameter that increases the smoothness switching surface.

The proposed swing-tracking control law depends on the sliding surface and the nonlinear system that can be derived as follows:

$$gn(S) = \lambda\dot{\theta} + h(-) + F(t)g(-) \qquad \ldots(8)$$

$$F(t) = \frac{\alpha sgn(S) - \lambda\dot{\theta} - h(-)}{g(-)} \qquad \ldots(9)$$

In order to find the expression $h(-)$ and $g(-)$, Eq. (2) is solving for $\ddot{\theta}$ and $\ddot{x}$ as follows:

$$\ddot{x} \quad \frac{gsin(\theta) - \ \ddot{\theta}}{\cos(\theta)} \qquad \ldots(10)$$

$$\ddot{\theta} \quad \frac{gsin(\theta) - \ddot{\ }\cos(\theta)}{} \qquad \ldots(11)$$

Then substituting Eqs. (10 and 11) into Eq. (1) as follows:

$$mlcos(\theta)\ddot{\theta} = F(t) - (M+m)\ddot{x} - \beta\dot{x} + mlsin(\theta)\dot{\theta} \qquad \ldots(12)$$

$$mlcos(\theta)\ddot{\theta} \quad F(t) - (M \quad)\frac{(gsin(\theta) - \ \ddot{\theta})}{\cos(\theta)} \quad \dot{x} \quad mlsin(\theta)\dot{\theta} \qquad \ldots(13)$$

$$mlcos(\theta)\ddot{\theta} - (M \quad m)\frac{\ddot{\theta}}{\cos(\theta)} \quad F(t) - (M \quad m)\frac{gsin(\theta)}{\cos(\theta)} \quad \dot{x} \quad mlsin(\theta)\dot{\theta}^2 \ldots(14)$$

$$\ddot{\theta}\left(mlcos(\theta) - (M \quad m)\frac{}{os(\theta)}\right) \quad F(t) - (M \quad m)\frac{gsin(\theta)}{os(\theta)} \quad \dot{x} \quad mlsin(\theta)\dot{\theta} \qquad \ldots(15)$$

$$\ddot{\theta}(ml \qquad (\theta) - (M \quad m)l)$$
$$F(t)cos(\theta) - (M \quad m)gsin(\theta) \qquad s(\theta)\dot{x} \qquad s(\theta)sin(\theta)\dot{\theta}$$
…(16)

$$\ddot{\theta} \quad \frac{F(t)cos(\theta) - (M \quad m)gsin(\theta) - \quad s(\theta)\dot{x} \qquad s(\theta)sin(\theta)\,\dot{\theta}}{(ml \quad {}^2(\theta) - (M \quad m)l)} \qquad \ldots(17)$$

$$\ddot{\theta} \quad \frac{F(t)cos(\theta)}{ml(co \quad (\theta)-1)-} \quad \frac{-(M \quad m)gsin(\theta) - \quad s(\theta)\dot{x} \qquad s(\theta)sin(\theta)\,\dot{\theta}}{ml(co \quad (\theta)-1)-} \qquad \ldots(18)$$

From $\ddot{\theta}(-)$, the system parameters variation and the uncertainty make the inverted pendulum affect on the existence of the non-linearity degree, so there is a necessary need for the swing-tracking control algorithm, which enhances the performance of the overall nonlinear system.

Then,

$$\ddot{\theta}(\theta, \dot{\theta}, \dot{x}, F) = F(t)g(-) + h(-) \qquad \ldots(19)$$

Where

$$h(-) \quad \frac{-(M \quad m)gsin(\theta) - \quad s(\theta)\dot{x} \qquad s(\theta)sin(\theta)\,\dot{\theta}}{ml(co \quad (\theta)-1)-} \qquad \ldots(20)$$

$$g(-) \quad \frac{s(\theta)}{ml(co \quad (\theta)-1)-} \qquad \ldots(21)$$

Then, the proposed nonlinear swing-tracking control law based on sliding mode technique can be described by Eq. (22) in order to make the nonlinear system asymptotically stable and to find a smooth force control action.

$$F(t) \quad \frac{sgn(S) - \ \dot{\theta} - \frac{-(M+m)gsin(\theta) - \beta cos(\theta)\dot{x} + mlcos(\theta)sin(\theta)\,\dot{\theta}}{ml(cos^2(\theta)-1)-}}{\frac{cos(\theta)}{ml(cos^2(\theta)-1)-}} \qquad \ldots(22)$$

The control parameters (α and λ) can be adjusted by using a new proposed technique which is Bees-Slice Genetic algorithm.

Part #2

Bees-Slice Genetic algorithm (BSGA):

In this work, the proposed optimization algorithm (BSG) is a hybrid algorithm which consists of Bees algorithm [16 and 17] and Slice Genetic algorithm [18, 19 and 20].

The main advantages for this proposed optimization algorithm are to improve the problem of local search of the Bees algorithm by using Slice Genetic algorithm which has the capability of dividing the population (Recruit Bees) into slices and duplicating good individuals where the operation of dividing will lead to implementing the optimization in multi dimensions and this will speed up the process of optimization while the process of duplication will give high opportunity to good individuals to exhibit all the best traits especially when applying random crossover to it [18] while the problem of the global search in the SG algorithm modify by using BA which has the capability of combining the (Fittest Bees) and a new population of (Scout Bees) generating in the global search [16].

The proposed on-line auto-tuning algorithm is applied as a powerful optimization algorithm to determine the best parameters α and λ of the controller in order to improve the convergence characteristics and response accuracy by reducing the processing time and the tracking angle error for the inverted pendulum system thus, the BSGA will be employed to tune the control parameters of the nonlinear controller.

The proposed tuning steps of the nonlinear controller parameters by using BSGA can be described in detail as follows:

Step 1: Generated randomly values of the control parameters as the initial population for (n) Scout Bees as a global search.

Step 2: The fitness of the (n) population is evaluated as Eq. (23) that is taken from [18]:

$$fitness = \frac{1}{objectivefunction + \sigma} \quad \ldots(23)$$

σ : is a constant value and large than zero to avoid division by zero.

Objective function: is mean square error as Eq. (24).

$$-\sum \quad [(\theta \qquad \theta) \quad (\dot{\theta} \qquad \dot{\theta}) \quad \ldots(24)$$

N: is the number of iteration.

Step 3: In the neighborhood search as a local search, chosen the number of slice depends on the number of the highest fitness for the Scout Bees (population) as (m) Selected Bees.

Step 4: Initialize randomly (m) slices for the Recruit Bees (population) with dimension [a ×b].

a: is the number of the Recruit Bees in each slice.

b: is the number of control parameters (λ and α).

Step 5: Determine the size of neighborhood (patch size) by applying the proposed Eqs. (25 - 28) as follows:

$$m(0,1) \quad \ldots(25)$$

$$\ldots(26)$$

$$m(0,1) \quad \ldots(27)$$

$$\ldots(28)$$

Step 6: Generated Recruit Bees depend on Eqs. (26 and 28) more Bees in order to search near to the best control parameters (α and λ) in order to fill all slice $[m]_{(a\times b)}$.

Step 7: The fitness of each slice individual is calculated.

Step 8: For each slice vertically find the global maximum fitness by using Eq. (23).

Step 9: In the horizontal, the optimal solution for all slices is found.

Step 10: The individual horizontal is duplicated based on maximum fitness of the horizontal.

Step 11: Put a parameters as in Classic GA.

Step 12: Apply arithmetic random crossover with crossover probability 0.85 (this will let the duplicated individuals produce their best).

Step 13: Apply mutation as in Classic GA with mutation probability of 0.01.
Step 14: The fitness vertically is calculated then for global maximum fitness, found the slices.
Step 15: Find the optimal solution for all slices in the horizontal.
Step 16: By comparing step 16 to step 9 to find the optimal global solution.
Step 17: Compare individual's fitness in the current generation, with the previous one, and then pick out the highest fitness for the Recruit Bees.
Step 18: Repeat Steps (11 to 17) until the stopping criterion is satisfied for the local search.
Step 19: Chosen the highest fitness for the Recruit Bees as Fittest Bees in each slice.
Step 20: Return to global search by assign the (n-m) remaining Bees to random search and new population of Scout Bees are generated.
These steps of the optimization algorithm for the control parameters are repeated for each sample (on-line), where the sampling time is equal to 0.01 second.

Simulation Results And Experimental Work
The finite difference method is applied with sampling time equal to 10 mSec in order to solve the nonlinear dynamic inverted pendulum equations that is described in section 2 is verified by using the MATLAB package and specification parameters of the inverted pendulum model are taken from [15].
The swing-tracking tuning control algorithm which is proposed in section 3 are tuned the control parameters of the nonlinear controller by using Bees-slice genetic algorithm steps mentioned above.
In order to achieve the proposed tuning swing-tracking control algorithm, there are many parameters of the algorithm should be defined as table 2.

Table (2) The parameters of proposed tuning algorithm

Description	Value
The number of the Scout Bees (n) in the global search.	10
The number of slice (m) is equal to the number of Selected Bees.	4
The number of Recruit Bees in each slice.	10
The number of weights in each Bee.	2
The population size in the local search.	40
The crossover probability.	0.85
The mutation probability.	0.01
The number of Fittest Bees.	4
The number of iteration (N) in the global search.	5
The number of iteration (P) in the local search.	5
The value of (μ) for increasing the smoothness switching surface.	25

From Figure (3-a) the Matlab simulation results for the proposed nonlinear controller of the pendulum angle swing-tracking based on sliding mode control with on-line BSGA, show excellent angler position tracking performance of the pendulum with initial angle equal to -0.2 radian and the time response specification of 0.73 sec rising time, 1.0 sec settling time and no overshoot at transient state then at steady-state the output pendulum angle approaches to zero radian when the desired pendulum angle is zero radian at inverted position.

Figure (3-b) indicates the convergence of the angle error for the inverted pendulum motion where the maximum value of the angular error is 0.2 radian at the transient state response while it is clear at steady-state, the error approximates to zero radian that means the pendulum is stabilized at inverted position.

Figure (3-c) shows effectiveness performance of the proposed tuning swing-tracking control algorithm in terms of generating smooth values of the force control input without sharp spikes as well as no saturation state in the control action because the BSGA has the capability to find and tune the values of the nonlinear controller parameters. So the maximum and minimum force control action value is (5 and -5) N respectively at transient state that lead to keeping the position output of pendulum in the upright position.

Figure (3-d) demonstrates the motion of the cart position that it moved from zero position and stopped at position 0.47 m.

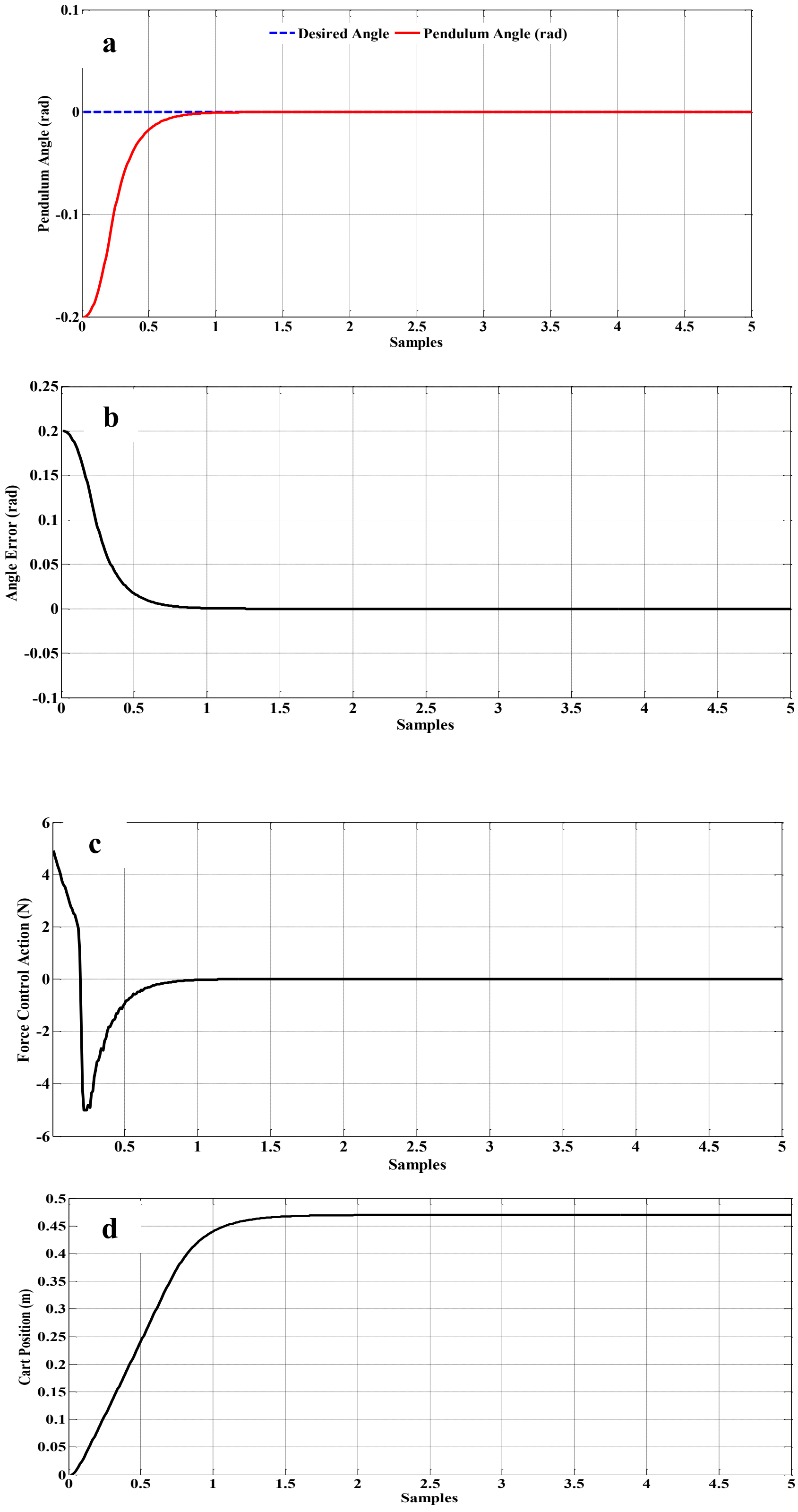


Figure (3): Simulation results (a) angle output for pendulum; (b) pendulum angle error; (c) force control action; (d) cart position.

The MSE of the on-line global search for angle and angular velocity errors for the inverted pendulum motion at each sample is shown in Figure (4).

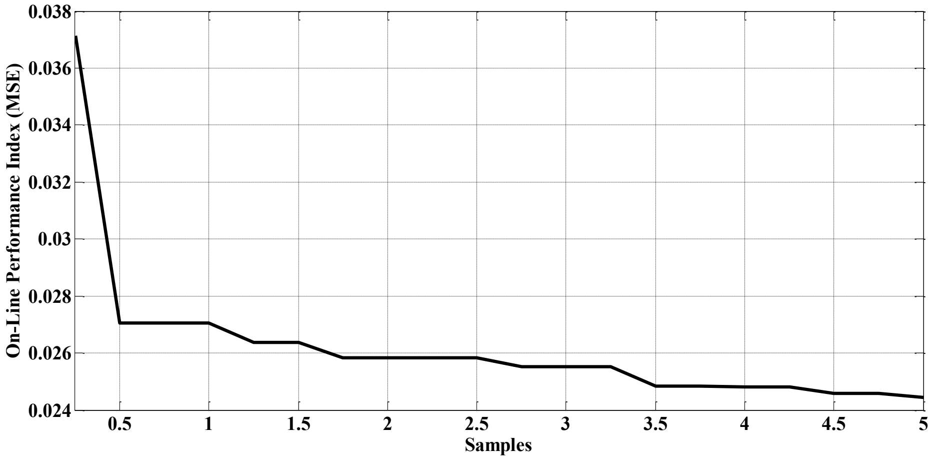


Figure (4): The performance index (MSE).

Instantaneous control parameters α and λ of the proposed controller are shown in Figure (5) which are found and tuned by using BSGA in order to reduce and overcome the chattering phenomena of the sliding mode control and to find the best force control action.

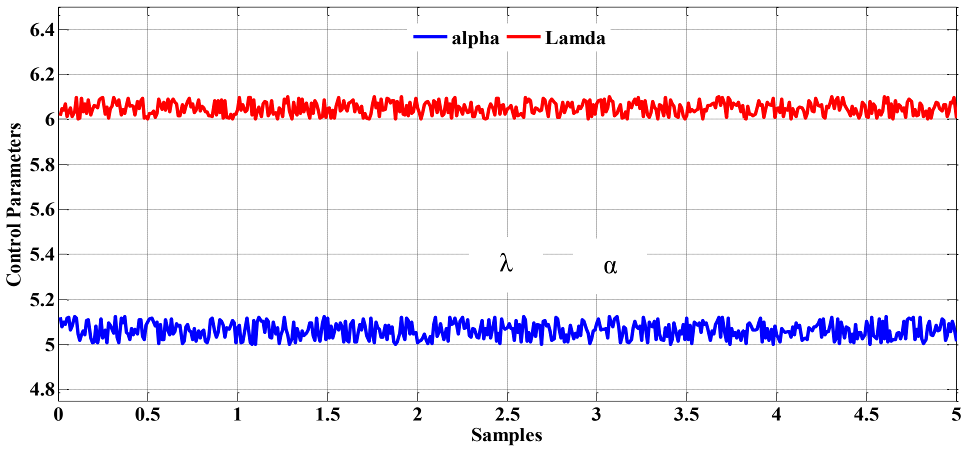


Figure (5): The control parameters λ and α.

Figure (6) shows the phase-plane plot to observe the stability of the closed loop feedback nonlinear swing-tracking controller for inverted pendulum system and to focus on the chattering effect that has been eliminated clearly for these reasons: it is used Sigmoid function as a Signum function and the value of control parameters are determining on-line by using BSG

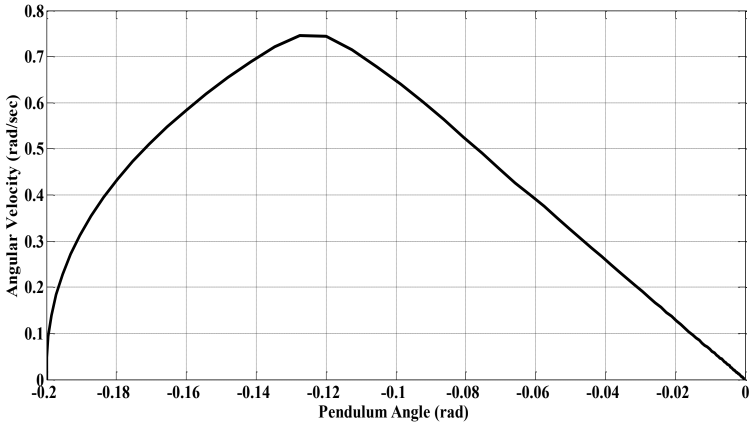
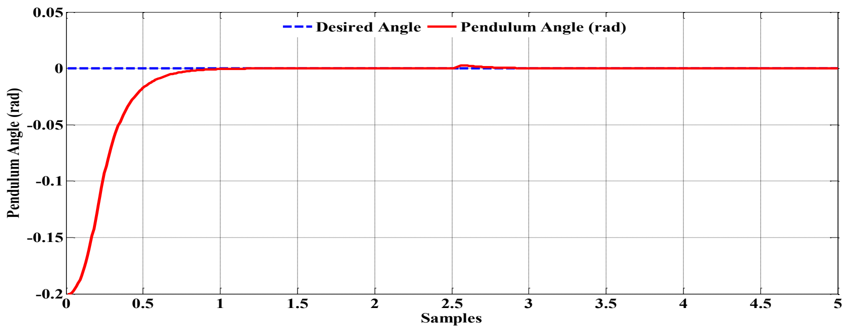
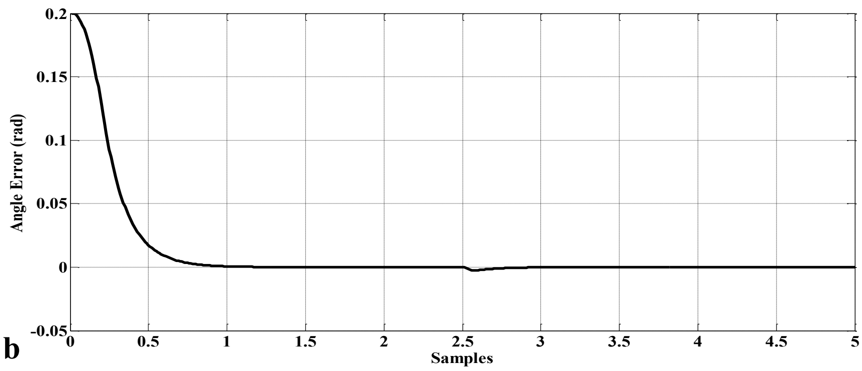


Figure (6): The phase-plane plot pendulum angle against angular velocity.

In order to investigate the nonlinear controller has a capability of adaptation performance and robustness ability by adding undesirable boundary disturbances to the pendulum. Figures (7- a, b, c and d) shows reasonable position tracking performance of the pendulum during addition of undesirable boundary disturbances (3) N at time between (2.50 to 2.55) second.



a



b

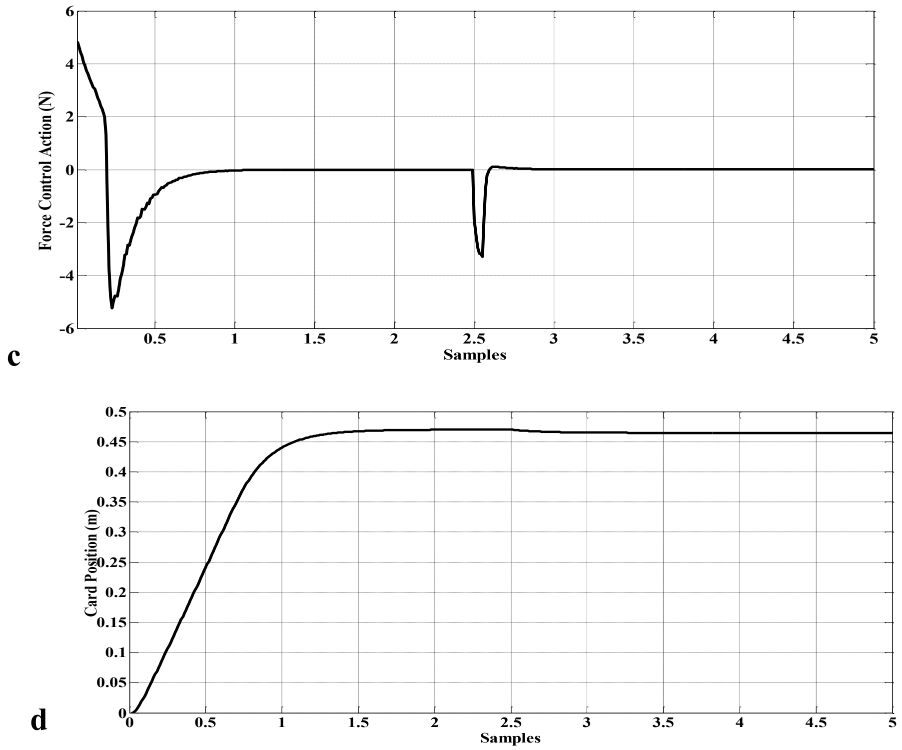
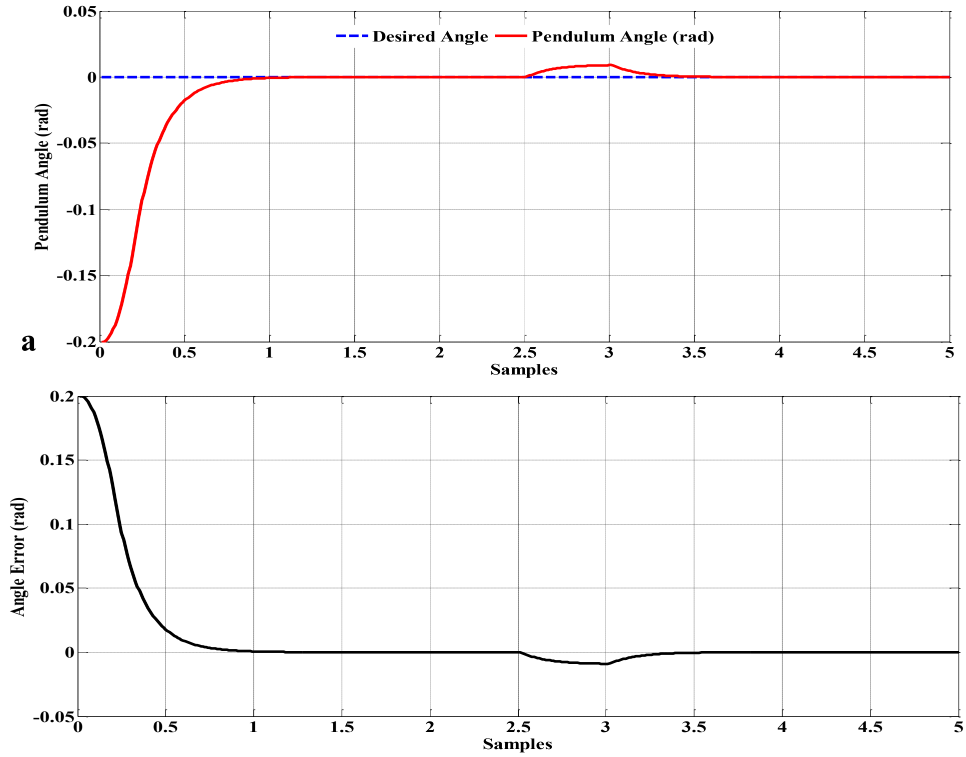


Figure (7): Simulation results with undesirable boundary disturbances (a) angle output for pendulum; (b) pendulum angle error; (c) force control action; (d) cart position.

Figures (8- a, b and c) shows reasonable position tracking performance of the pendulum during adding undesirable boundary disturbances (3) N at time between (2.50 to 3.00) second to investigate the robustness and adaptation performance of proposed nonlinear controller.



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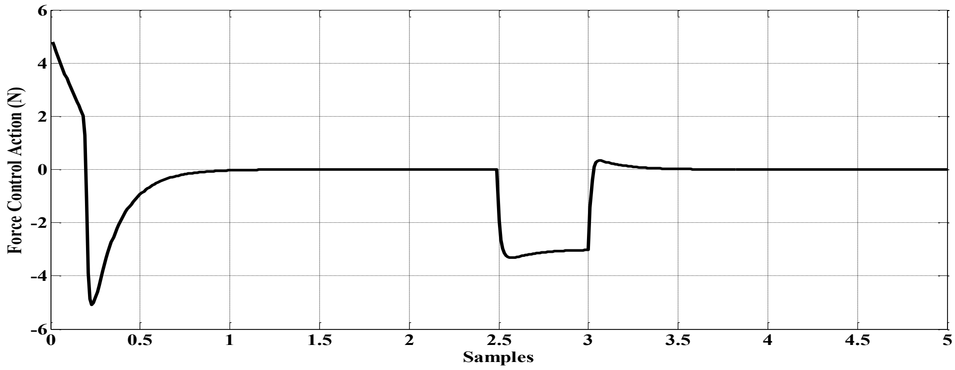

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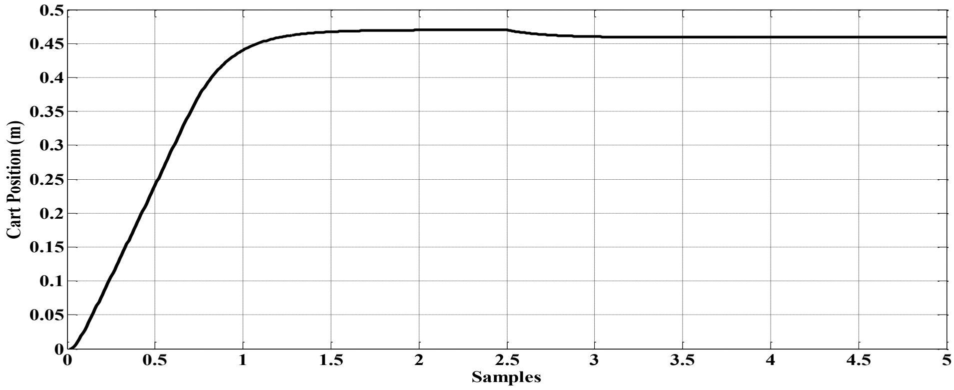
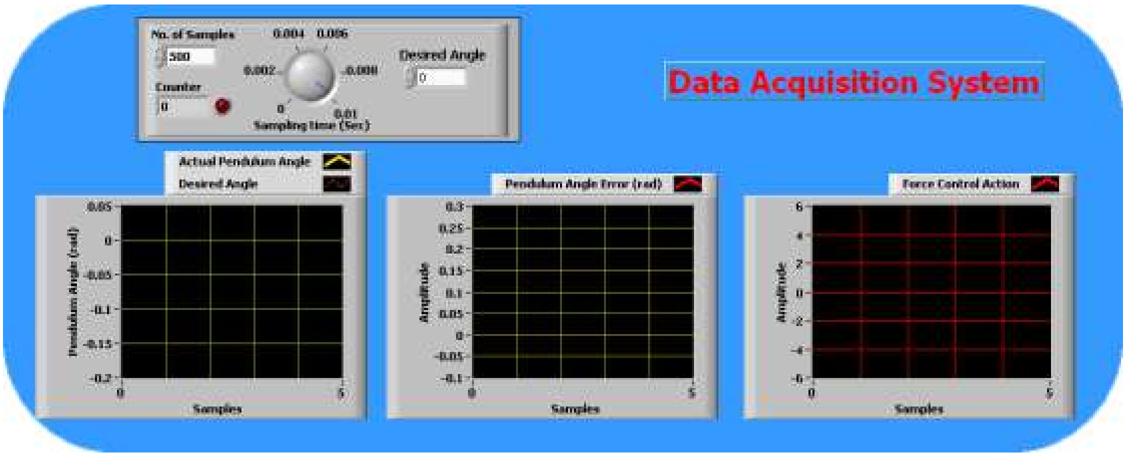


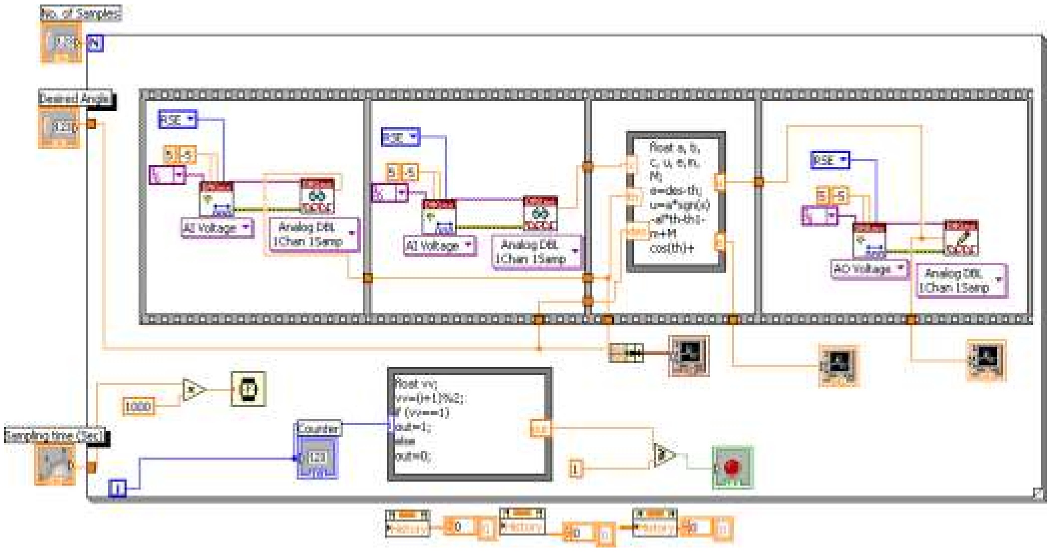
d

Figure (8): Simulation results with undesirable boundary disturbances (a) angle output for pendulum; (b) pendulum angle error; (c) force control action; (d) cart position.

To verify the applicability and the performance of the proposed on-line auto-tuning nonlinear controller with BSGA, experiments are conducted on inverted pendulum with a LabVIEW guide package. The front panel and the block diagram of the proposed control algorithm have been written in the LabVIEW, as shown in Figures (9-a and b) respectively.

a





(b)

Figure (9): LabVIEW package (a) the front panel of the data acquisition system of the nonlinear swing angle controller; (b) the block diagram of the proposed nonlinear controller.

Figure (10-a) shows the experimental result for the response of the pendulum angle and it is reasonable position tracking performance with initial angle equal to -0.2 radian and it is clear, there are very small swing at inverted position (desired angle) of the pendulum that caused the angle error as shown in Figure (10-b) therefore the force control action as shown in Figure (10-c) has small sharp spikes around state-steady in order to track the error and to stabilize the pendulum at inverted position.

In fact, the main core that causes the difference between simulation and experimental results are two errors: modelling errors which incomplete knowledge about system components and residual errors due to the presence of inherent friction in the real system.

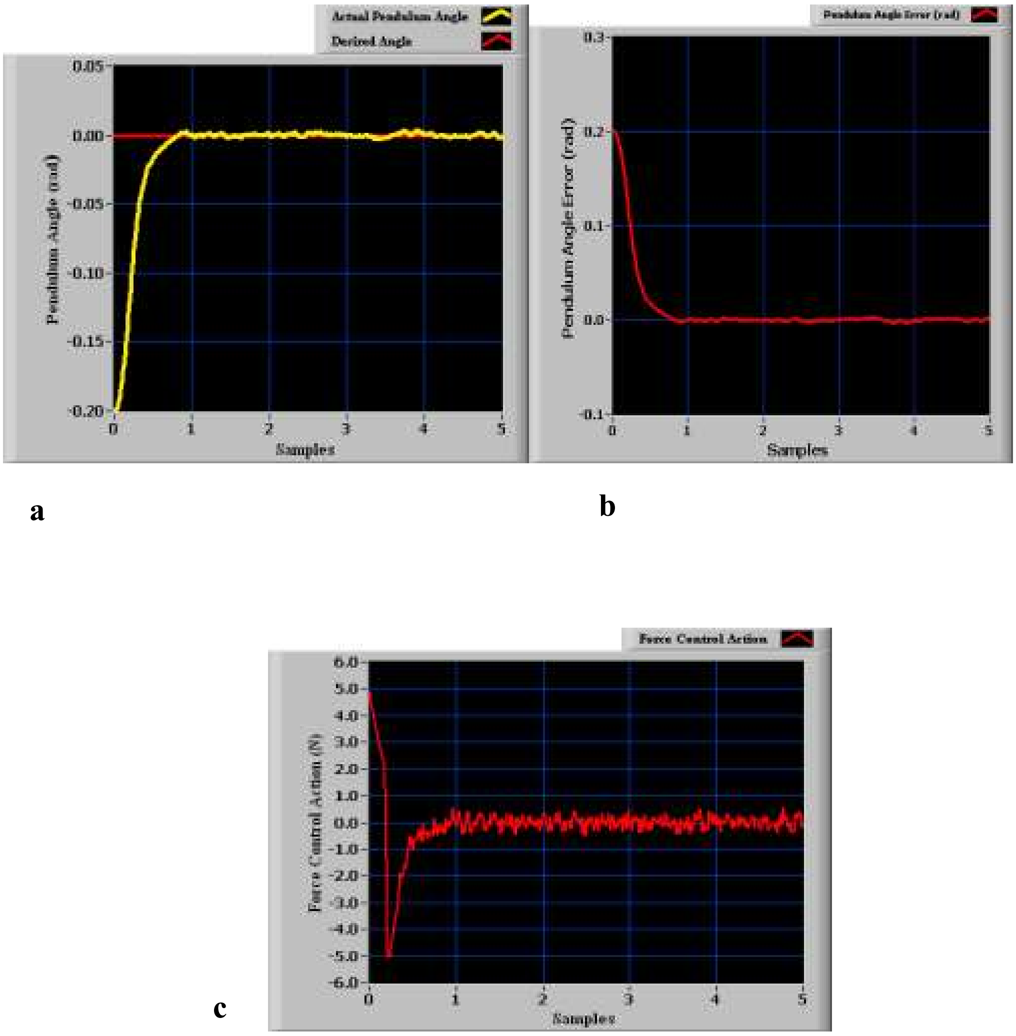


Figure (10): Experimental results (a) angle output for pendulum; (b) pendulum angle error; (c) force control action.

CONCLUSIONS

The simulation results and the experimental work on the BSGA tuning control algorithm of nonlinear swing-tracking controller are based on sliding mode control with Lyapunov method presented in this paper for the nonlinear inverted pendulum system which shows preciously that the proposed tuning swing-tracking control algorithm has the following capabilities of:

- High computational accuracy and stable on-line auto-tuning control parameters with fast fitness evaluations.
- Generating smooth and optimum suitable force commands, without sharp spikes as well as no saturation state.
- Minimizing the swing-tracking angle error of the pendulum at inverted position.
- Elimination the chattering phenomena of the sliding mode control.
- Robustness and adaptation performance when undesirable boundary disturbances have been added to the system.

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