Received: 9 October 2023 | Revised: 3 December 2023 | Accepted: 21 December 2023
DOI: 10.37917/ijeee.20.2.19 Vol. 20 | Issue 2 | December 2024

Open Access

Iraqi Journal for Electrical and Electronic Engineering
Original Article

IJEEE University of Basrah College of Engineering

Design of Optimal STSMC Method Based on FPGA to Track the Trajectory of 2-DOF Robot Manipulator

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Abstract
This article emphasizes on a strategy to design a Super Twisting Sliding Mode Control (STSMC) method. The proposed controller depends on the device of Field Programmable Gate Array (FPGA) for controlling the trajectory of robot manipulator. The gains of the suggested controller are optimized using Chaotic Particle Swarm Optimization (PSO) in MATLAB toolbox software and Simulink environment. Since the control systems speed has an influence on their stability requirements and performance, (FPGA) device is taken in consideration. The proposed control method based on FPGA is implemented using Xilinx block sets in the Simulink. Integrated Software Environment (ISE 14.7) and System Generator are employed to create the file of Bitstream which can be downloaded in the device of FPGA. The results show that the designed controller based of on the FPGA by using System Generator is completely verified the effectiveness of controlling the path tracking of the manipulator and high speed. Simulation results explain that the percentage improvement in the Means Square Error (MSEs) of using the STSMC based FPGA and tuned via Chaotic PSO when compared with the same proposed controller tuned with classical PSO are 17.32 % and 13.98 % for two different cases of trajectories respectively.

Keywords
DOF Robot Manipulator, Lyapunov Theorem, FPGA, STSMC, Chaotic PSO.

I. INTRODUCTION

The robotics is a science which deals with many scopes such as the design, the controlling as well as modeling of robot. Nowadays the robots may be utilized everywhere in the daily life, where they can be used in different life jobs and industry. The utilization of robot is very wide, so, there are many different types of robots such as rectangular, revolute, spherical, horizontal jointed and cylindrical which used in manufacturing and industry. The robots may be used to supply the desired motion in the processes of manufacturing like drilling, painting, pick, cutting, milling and welding, etc. The configuration of two link robot manipulator with 2 Degrees of Freedom (2 - DoF) is generally well proper to insert and assemble the small parts such as electronic components. In spite of the major goal is to manufacture, design and control the real robotics, but it is important to perform the simulations to real robots. Simulations are characterized with they are less expensive, easier to setup, faster and more proper to use. The simulation of robots allows with better design by choosing the best and suitable values of parameters for the designed system.

The accumulate and multiply are the most operations which used in the control calculations. When any type of digital controller is dealing with such operations, so, the computational overhead will be reached to the maximum. The speed and the sampling rate will be limited by the system rate which performs such operations. The control system speed has influence on many matters like, its performance, robustness, stability, and the characteristics of disturbance rejection, so, the FPGAs represent the good choice.

The FPGAs characterized by its fast and the rate of control loop is only limited by actuators, sensors, and I/O modules [1]. Other features make the FPGAs the best choice to implement different digital controllers are data parallel processing and width of configurable word [2]. System Generator is a modeling tool of system level which simplifies the design of FPGA hardware. The designer which has a less knowledge about the hardware of FPGA can use this tool and develops Simulink in different ways to obtain the modeling environment which may be suitable for hardware design [3].

II. Literature Revirw

There are many studies to deal with controlling of robot manipulators. PID Control method is one of most control used scheme in the world because of its simplicity to control many applications. This controller consists from three parameters (Proportional, Integral and Derivative) which tuned to achieve better control performance. In [4], the dual PID control method was designed and found that it was an effective scheme to minimize the overshoot and save electrical energy consumption in tracking the path of robot. The PID controller was proposed in [5] to control the robot manipulator, where the gains of PID was optimized via using whale algorithm. The simulation results demonstrated the superiority of the optimal controller with a good settling time. The controlling of input factors and tracking error had been employed to examine the robustness of PID control strategy in controlling the trajectory of (2 Links) robot manipulator, the results achieved the stability requirements [6]. In the literature [7], the Fuzzy Sliding Mode Control (SMC) parameters in the sliding surface were obtained by using developed Particle Swarm Optimization (PSO). The control requirements were achieved to track the robots, where the gains of state feedback calculated via using the linear quadratic regular method. An optimal SMC was introduced to track the biped robot, the controller was tuned with PSO. The results explained that the convergence range for the proposed controller were enhanced simultaneously [8]. In the literature [9], Linear Quadratic Regulator (LQR) control was suggested to simulate the correction of inputs and predict the successful rate for the robot manipulator to pick up its target through the motion and the sensor errors. The simulation and experiments outcomes demonstrated the effectiveness of the proposed method. A multi group PSO algorithm was proposed to track the motion planning of robot manipulators. Some of best particles were chosen from the branch groups instead of bad particles from elite group. Simulation results shown that the suggested algorithm was superior with other algorithms and it was converged toward the optimum [10]. In [11], SMC scheme was designed to achieve anti-interference, vibration suppression and the tracking control for (2-DOF) joint rigid coupling manipulator under the effect of bounded disturbance at the torques of input. The article proved the stability requirements by using Galerkin approximation sequences. In the literature [12], a new method of fuzzy logic controller proposed to track the path of (2-DoF) manipulator robot. The simulation results were developed by MatLab/Simulink software and compared with performance of conventional PID control method. The combination of the fuzzy variable acceleration improved the response of system. The tracking control for (2 - links) robot manipulators was presented in [13]. The robust tracking was achieved using Super Twisting SMC (STSMC), where the system stability was proved by depending on the theorem of Lyapunov. The Social Spider (SSO) algorithm employed to find the best optimal values for suggested method. The quality of the designed optimal control method was obtained and verified by using MATLAB software. The experimental outcomes conducted depending on (LabVIEW 2019) software. A Fuzzy, artificial immune system and Fractional Order (FOPID) control structure was designed in [14] for controlling the movements of (2-DOF) robotic manipulator. The traditional clonal selection algorithm had been utilized to optimize the links motion. The proposed control strategy gave good outcomes. Authors in [15], proposed Clonal Selection algorithm to recognize the outline in mobile robots and based on the machine learning method of Artificial Immune Systems. The results shown that the robot was trained successfully. In the literature [16], a study combined both SMC and fuzzy system to improve the stability conditions and achieve the high-accuracy to control the (4 DoF) manipulator. The experimental results demonstrated that the designed controller was fast, accurate and stable in controlling the robots of service. By increasing the manipulator links in the system, usefulness and efficacy were enhanced with the complexity. FOPID method was used to track the motion of (3 DoF) robot manipulator system. The outcomes explained the quality of the prepared controller [17]. In [18], adaptive fractional high order terminal SMC was proposed to track the motion of robotic manipulators under the effect of varying loads with external disturbances and uncertainties. The simulation results explained the robustness of the suggested scheme. The (STSMC) represents a strong second-order control method and has many features, like [19], [20]:

- The influences of chattering problem at the response output using STSMC will be avoided.
- The STSMC method needs only the sliding surface variable, and don't require its derivative.
- Within a finite time, the states of system will reach to the equilibrium point by using STSMC scheme.
- Finally, the STSMC satisfies exact convergence.

This work involves the control law development of the STSMC method depending on (2-DOF) manipulator. The asymptotic stability is proved by achieving the Lyapunov theorem of the controlled system. The proposed controller was implemented using FPGA depending on the Xilinx block sets using system generator through Integrated Software Environment (ISE 14.7) and MATLAB software. To address the design parameters problem by designing STSMC controller which based on FPGA which have direct effect on dynamic performance for the controlled robotic system, the optimization techniques are introduced to tune the parameters of a designed controller. In the present paper, the Chaotic PSO algorithm has been used to find the optimum gains of the proposed control scheme to improve its performance based on robotic system. The paper organizes as follows: the modeling of 2 - Links robot manipulator is presented in Sec. III. Sec. IV. describes the design of the proposed controller based on FPGA. Sec. V. is dedicated to employ the Chaotic PSO Algorithm to have the best optimal parameters of the suggested controller. Sec. VI. gives the simulation results for comparison purposes. Finally, the conclusions of this article are summarized in Sec. VII.

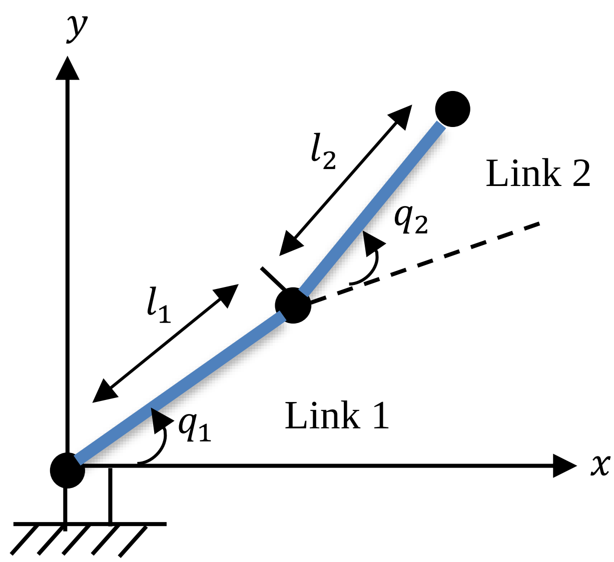


Fig. 1. Two – DoF Robot Manipulator Block Diagram

III. Modeling of 2 - links Robot Manipulator

As given in Fig. 1, the robot manipulator with (2 DoF) is a planar arm consisted from a (2 links) and revolute joint. Each link of manipulator is actuated through electrical motor, where, one is in an elbow and the other is in a base. Both axes and links of motor are directly connected. The manipulator arm has a planar motion in Cartesian directions (x - y) and it consists of two links, assumed to be rigid, with the masses (m_1, m_2) and lengths (l_1, l_2). The two joints positions have been implemented by the vector $q = [q_1 q_2]^T$. Aiming for suitable representation for the control methods application, the dynamic model for (2 links) manipulator can be demonstrated as [21]:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(\dot{q}) + u_d = u \tag{1}$$

The matrix of inertia $M(q)$ can be defined as:

$$M(q) = \begin{bmatrix} d_1 + d_2 + 2d_3\cos(q_2) & d_2 + d_3\cos(q_2) \\ d_2 + d_3\cos(q_2) & d_2 \end{bmatrix} \tag{2}$$

The vector of gravitational forces is $G(q)$ and defined as:

$$G(q) = \begin{bmatrix} d_4 g\cos(q_1) + d_5 g\cos(q_1+q_2) \\ d_5 g\cos(q_1+q_2) \end{bmatrix} \tag{3}$$

The vector $C(q,\dot{q})$ of Coriolis and centrifugal forces can be given as:

$$C(q,\dot{q}) = \begin{bmatrix} -d_3\dot{q}_2\sin(q_2) & -d_3(\dot{q}_1+\dot{q}_2)\sin(q_2) \\ d_3 q_1\sin(q_2) & 0 \end{bmatrix} \tag{4}$$

The vector (d) is computed as: $d_1 = (m_1+m_2)l_1^2$, $d_2 = m_2 l_2^2$, $d_3 = m_2 l_1 l_2$, $d_4 = (m_1+m_2)l_1$ and $d_5 = m_2 l_2$, where, $d = [d_1, d_2, d_3, d_4, d_5]$, so, d=[2.9,0.76,0.87,3.04,0.87]. The friction force is $F(\dot{q}) = 0.2sgn(\dot{q}_2)$.The torque ($u$) represents the control input which produces through the rotary electro hydraulic actuators at the robot joint. (u_d) is defined as the unknown disturbance, where, $u_d = [\ 0.2\sin(t)\ \ 0.2\sin(t)]^T$. Equation (1) can be rewritten as:

$$\ddot{q} = M(q)^{-1}[u - C(q,\dot{q})\dot{q} - G(q) - F(\dot{q}) - u_d] \tag{5}$$

The angular positions of robot are ($q_1$and q_2), their derivatives represent the angular velocity ($\dot{q}_1$and $\dot{q}_2$), Finally, the dynamic model should be rearranged considering the state variables as:

$$\frac{d}{dt}\begin{bmatrix} q_1 \\ q_2 \\ \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} = \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ M(q)^{-1}[\tau - C(q,\dot{q})\dot{q} - G(q) - F(\dot{q}) - \tau_d] \end{bmatrix} \tag{6}$$

IV. Design of the Proposed Controller Based on FPGA

The key objective for designing the controller for the robot manipulator is to satisfy the requirements of stability to track the desired path of robot with minimum vibration, thus a robust controller with accurate specifications is needed for such objectives. A control method will be proposed to achieve such requirements efficiently. The controller has been shown in Fig. 2, where it involves of two sub control strategy, one to each joint of the robot manipulator. As shown in Fig. 2, the proposed controller is designed using Xilinx block. In the proposed controller, STSMC is employed to limit the output chattering problem as well as the nonlinearity. The controller is designed for controlling the torque which produces through the rotary actuators on the robot joint.

The sliding surface at each joint for the vector $s=[s_1\ s_2]^T$ can be represented as:

$$s=\dot{e}+ce \tag{7}$$

Where, the error (e) is the difference between the desired and actual positions (q_d and q) respectively, where, $e=q_d-q$, and the variable (c) is an integer positive parameter. The equation (4) may be derived to give the following relation:

$$\dot{s}=\ddot{e}+c\dot{e}=\ddot{q_d}-\ddot{q}+c(\dot{q_d}-\dot{q}) \tag{8}$$

Substituting equation (5) into (8), we have:

$$\dot{s}=c(\dot{q_d}-\dot{q})+\ddot{q}-M(q)^{-1}[u-C(q,\dot{q})\dot{q}-G(q)-F(\dot{q})-u_d] \tag{9}$$

The control signal (u) of the STSMC method consists from two terms, the first one refers to the switching (u_sw) and the other is the equivalent (u_eq), so, the control input can be represented by:

$$u=M(q)(u_sw+u_eq) \tag{10}$$

The equivalent law can be denoted as:

$$u_eq=c(\dot{q_d}-\dot{q})+\ddot{q}-M(q)^{-1}C(q,\dot{q})\dot{q}+M(q)^{-1}G(q) \tag{11}$$

The switching law design is derived from the control law [22] and written as:

$$u_swi=-k_i\sqrt{|s_i|}sign(s_i)-b_i\int sign(s_i)dt \tag{12}$$

Where, $i=1,2$ and refers to each joint of the robot manipulator and the parameters (k_i,$b_i>0$). The control signal law can be obtained by substituting the equations (11) and (12) in equation (10), so the final control output follows:

$$u=M(q)[c(\dot{q_d}-\dot{q})+\ddot{q}-M(q)^{-1}C(q,\dot{q})\dot{q}+M(q)^{-1}G(q)+u_swi] \tag{13}$$

Substituting the equations (13) in equation (9) to get:

$$\begin{aligned}\dot{s}=[&-k_1\sqrt{|s_1|}sign(s_1)-b_1\int sign(s_1)dt\\ &-k_2\sqrt{|s_2|}sign(s_2)-b_2\int sign(s_2)dt]+z\end{aligned} \tag{14}$$

Where, z=$[z_1\ z_2]^T=(M(q)^-1F)^T$. In order to achieve the stability requirements in designing the STSMC method, the Lyapunov criteria method is applied. The derivative of quadratic Lyapunov function ($V=\frac{1}{2}ss^T$) is denoted in the sliding surfaces term as 23:

$$\dot{V}=s_1\dot{s_1}+s_2\dot{s_2} \tag{15}$$

Merging the equations (14) and (15) to be:

$$\begin{aligned}\dot{V}=&s_1[k_1\sqrt{|s_1|}sign(s_1)-b_1\int sign(s_1)dt+z_1]\\ &+s_2[k_2\sqrt{|s_2|}sign(s_2)-b_2\int sign(s_2)dt+z_2]\end{aligned}$$

Or, the term can be defined as:

$$\begin{aligned}\dot{V}\le&-k_1\sqrt{|s_1|}|s_1|-|s_1|\int b_1dt+|s_1|z_1\\ &-k_2\sqrt{|s_2|}|s_2|-|s_2|\int b_2dt+|s_2|z_2\end{aligned} \tag{16}$$

$$\begin{aligned}\dot{V}\le&-k_1\sqrt{|s_1|}|s_1|-|s_1|\int(b_1-\delta_1)dt\\ &-k_2\sqrt{|s_2|}|s_2|-|s_2|\int(b_2-\delta_2)dt\end{aligned} \tag{17}$$

The stabilization requirements to track the path of the robot manipulator will guaranteed if both ($b_1$and b_2) have values achieving ($b_1>\delta_1>|\dot{b_1}|$ and $b_2>\delta_2>|\dot{b_2}|$). Achieving the conditions (V) is a positive definite while $(\dot{V})$ is a negative definite for (t→0). Also, the sliding surfaces will converge to zero values as (t→ ∞).

The System Generator represents a Xilinx toolbox which can generate the Hardware Description Language (HDL) code in the Simulink environment automatically. The parameters of STSMC scheme is optimized using the Chaotic PSO algorithm to evaluate the controller output results. Then the controller is designed using Xilinx block sets which supported in Simulink environment as shown in Fig. 3. The quantization size of the block sets of the inputs is computed by in Gateway. Similarly, the size of output is implemented as Mult and AddSub blocks. In these blocks, the FPGA device type has been selected, clock period of FPGA, the kind of generated code (VHDL or Verilog) and other different desired features. By implementation the STSMC method in any (FPGA) kit system, the FPGA boundary dependent on the architecture by using the (In) and (Out) gateways. The function of Gateway block (In) is represented by conversion the floating point into fixed- point, where that FPGA will process it. The Gateway block (Out) translates the data of FPGA into floating point [24].

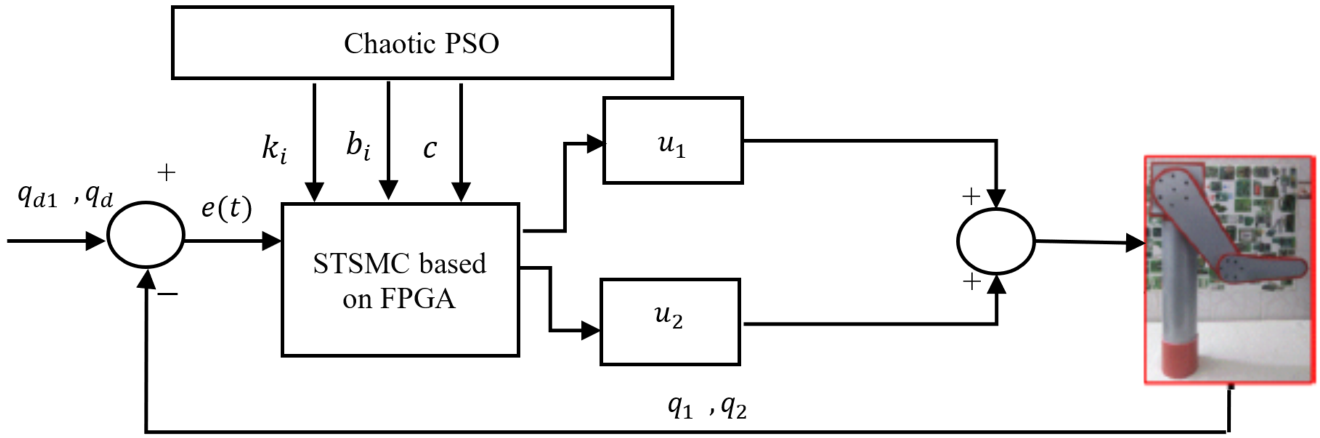


Fig. 2. Structure of 2 – DOF Robot Manipulator controlled via Optimal STSMC

V. Chaotic PSO Algorithm

The efficiency and the stability requirements must be achieved to the closed loop designed STSMC method to track the desired path of robot manipulator, three gains of the proposed controller (c, k as well as b) at each link of the robotic system musted be optimized. The trial and error method to adjust the controller parameters is not practical method, so, it is improper to obtain the controller optimal values. The traditional (PSO) algorithm is generally used a random sequence values to tune the parameters. First, the population solutions are initialized using PSO algorithm which is known a particle. Assume, the search space with D-dimension and N particles. For (i^{th}) iteration, the position ($x_i(t)$) and velocity ($v_i(t)$) of particle is denoted respectively as [25]:
$x_i(t) = x_i1, x_i2, x_i3, \ldots, x_{iD}$
$v_i(t) = v_i1, v_i2, v_i3, \ldots, v_{iD}$

The best position which is reached by the (i^{th}) particle and denoted as ($p_i = p_{i1}, p_{i2}, p_{i3}, \ldots, p_{iD}$), called ($p_{best}$). The all swarm then reaches to the global best position (g_{best}) and defines as ($p_g = p_{g1}, p_{g2}, p_{g3}, \ldots, p_{gD}$). The position and velocity of particle are computed in the next iteration as the following:

$$x_i(t+1) = x_i(t) + v_i(t) \tag{18}$$

$$\begin{aligned} v_i(t+1) &= a_1 r_1 (p_{besti}(t) - x_i(t)) \\ &+ a_2 r_2 (g_{besti}(t) - x_i(t)) + w v_i(t) \end{aligned} \tag{19}$$

Where (w) represents the weight factor of inertia, $w = 0.9$ [26], (a_1, a_2) are the coefficients of acceleration and the random values are (r_1, r_2) within the range [0,1]. The values of (w, r_1 and r_2) are the main factors that influnced the convergence behavior [27]. In the present paper, chaotic PSO algorithm is applied for finding the optimum values of the STSMC strategy to achieve the best performance of (2-DOF) robot manipulator. In the Chaotic PSO algorithm, the parameters (a_1, a_2) will be modified by employing the logistic map depending on the equation:

$$L(t+1) = \mu \times L(t) \times (1 - l(t)) \quad 0 \leq M(t) \leq 1 \tag{20}$$

Where $L(t)$ generated randomly and μ =4 [26]. Then, the new modification of velocity has been given as:

$$\begin{aligned} v_i(t+1) &= r_1 (p_{besti}(t) - x_i(t)) \times w v_i(t) L(t) \\ &+ (1 - L(t) \times r_2 (g_{besti}(t) - x_i(t)) \end{aligned} \tag{21}$$

The objective function depends on decreasing the cost function which is given in:

$$CostFunction = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_1^2} + \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_2^2} \tag{22}$$

Where, the (e_1, e_2) are the errors at each link of manipulator. The chaotic PSO algorithm is characterized with many advantages such as the easy implementation, the superior speed of search and the shortest time for running. The steps of chaotic PSO algorithm can be represented in the flowchart given in Fig. 4.

VI. Simulation Results

The computer results for designing the optimal STSMC scheme depending on the FPGA in Xilinx block sets are presented to track the desired path of the robot manipulator system. The quality of the proposed controller is verified within the MATLAB/SIMLINK toolboxes environment and ISE (14.7) software.

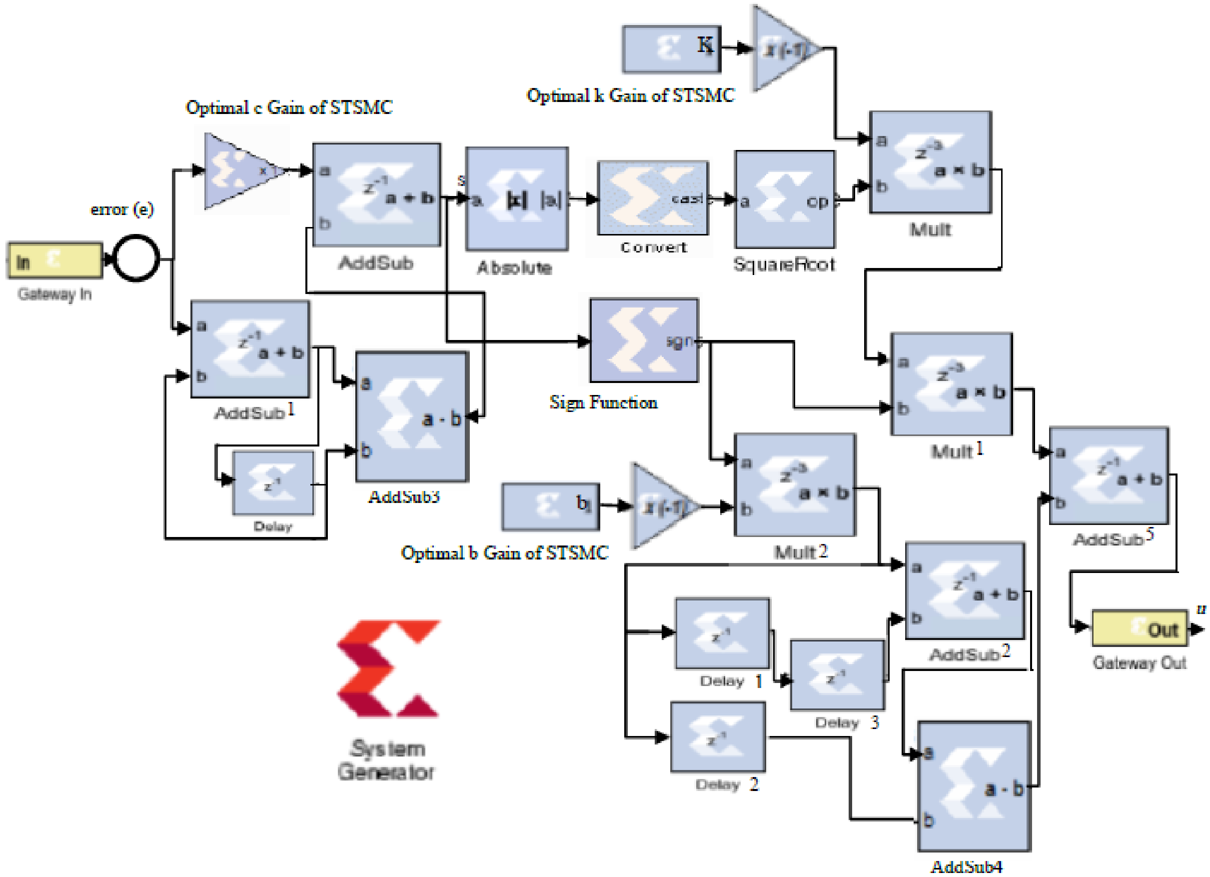


Fig. 3. Design of Optimal STSMC based on FPGA device.

The parameters of the suggested controller that controlled the robot manipulator at each link is optimized using Chaotic PSO algorithm. Fig. 5 demonstrates the fitness function of both traditional and chaotic PSO techniques within (100) iterations at each robot manipulator joint.

From Fig. 5, it is clear that the Chaotic PSO algorithm gives a good optimization than the classical PSO algorithm. The optimum parameters of the proposed control method are listed in Table (1). Three trajectories are chosen to test the effectiveness of the presented controller using FPGA device to track the path of the robot manipulator. Two trajectories are used to test the quality of the proposed control method based on FPGA device to the robot manipulator expressed as:

- $q_{1d} = 1 - e^{-2t^2}\cos(t), q_{2,d} = 1 - e^{-2t^2}\cos(2t)$
- $q_{1d} = 1 - \cos(t), q_{2,d} = 1 - \cos(2t)$

First trajectory results are given in Fig. 6 and these results demonstrates the desired and actual position controlled by the STSMC based on FPGA using Classical and Chaotic PSO algorithm at each link of the robot. The comparison results explain the actual trajectory will effectively close to the desired one using the Chaotic PSO algorithm.

TABLE I.
OPTIMUM PARAMETERS OF THE STSMC BASED ON FPGA

The Parameters at each link	Classical PSO	Chaotic PSO
c_1	139.86	133.01
k_1	144.56	149.14
b_1	67.55	112.46
c_2	119.39	98.99
k_2	138.37	95.08
b_2	67.48	88.21

Fig. 7 shows the angular position at each link of the robot manipulator to track the second trajectory. The results explain the goodness of the optimal STSMC based on FPGA

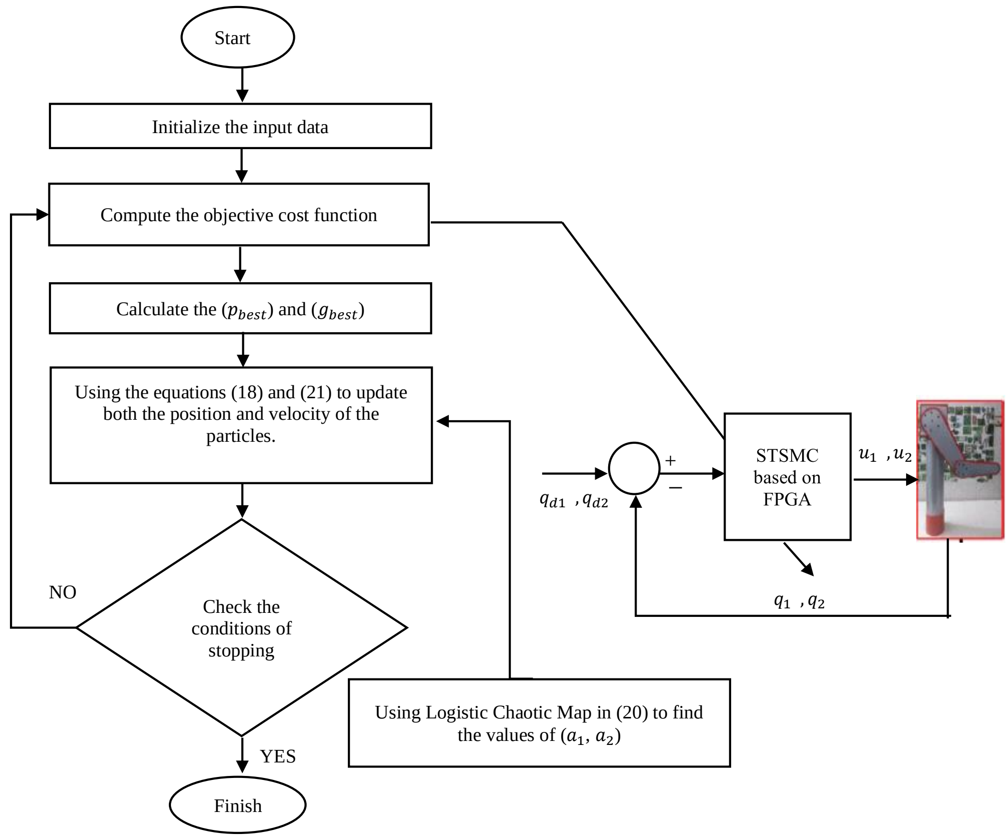
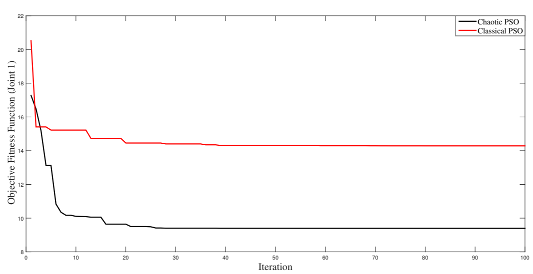
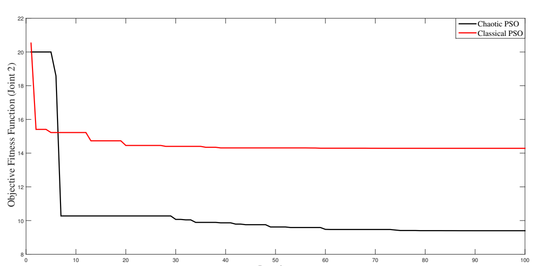


Fig. 4. Flowchart of Chaotic PSO Algorithm to Tune Parameters of STSMC Depends on FPGA.

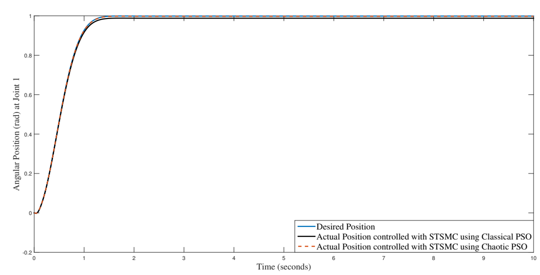


(a)

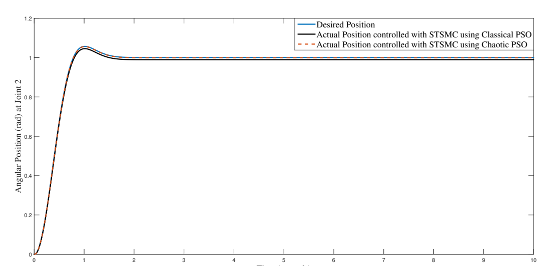


(b)

Fig. 5. Behaviors of Fitness function based on Classical and Chaotic PSO at (a) q_1, and (b) q_2.

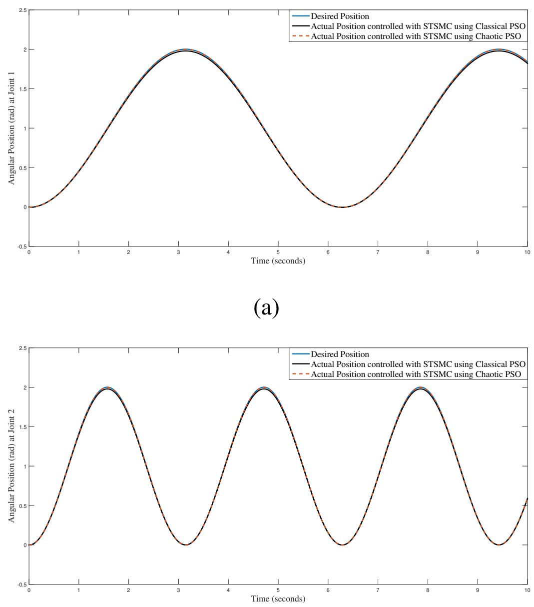


(a)



(b)

Fig. 6. For the First Trajectory: Actual and desired positions for both links using STSMC based FPGA.



(a)

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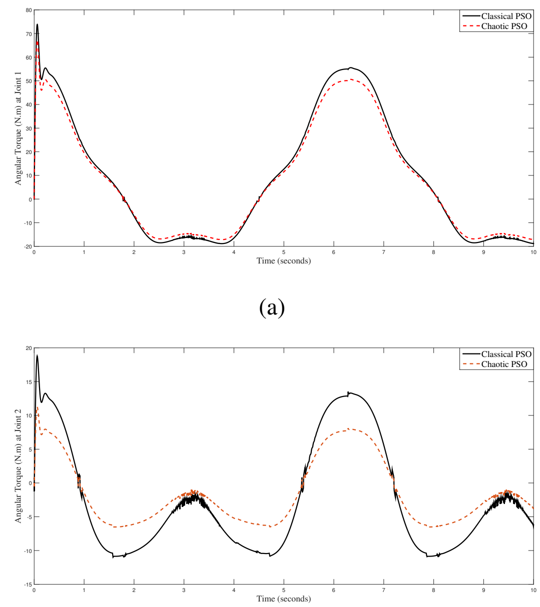
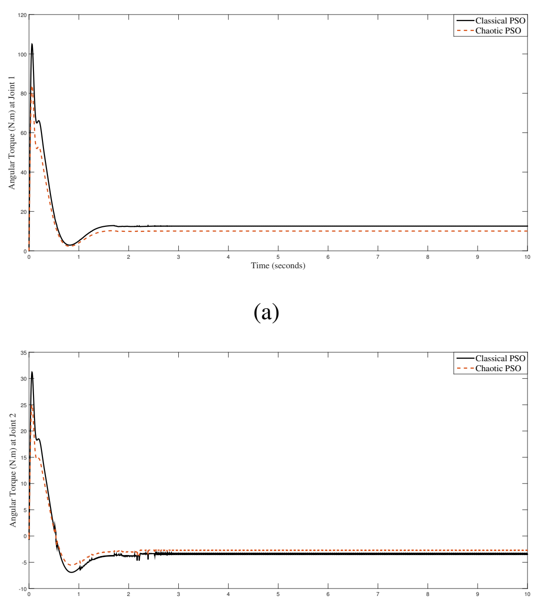
Fig. 7. For Second Trajectory: Actual and desired positions for both links using STSMC based FPGA.



(a)

(b)

Fig. 9. For Second Trajectory: Angular Torque at each link using STSMC based FPGA.



(a)

(b)

Fig. 8. For First Trajectory: Angular Torque at each link using STSMC based FPGA.

and Chaotic PSO algorithm to reach to the desired path rather than of using the classical PSO technique.

The control signal represents the angular torque at each link of the robot and shows in Fig. 8 and Fig. 9 for the first and second trajectories respectively. These Figures explain that we need a less torque using the proposed controller that tuned with Chaotic PSO algorithm in comparison with the optimal controller based on the classical PSO algorithm.

VII. Conclusions

In this paper, the STSMC technique for tracking the path of (2 - links) robot manipulator has been implemented by using FPGA due to many advantages like its high capacity of data storage, high speed to execute the operation and low energy consumption. The asymptotic stability has been proved in designing the STSMC method. Instead of depending on the trial and error technique to compute the optimal parameters of the designed controller, Chaotic PSO technique used and compared with the traditional PSO tuner to obtain best optimum parameters of the proposed control scheme. A best dynamic performance for the system has been obtained and the computer results in MATLAB/ SIMULINK and XILINX block sets proved that from the comparative study between both Chaotic and classical PSO algorithms. The simulation results demonstrated the efficiency of the STSMC method based on FBGA device and achieve the superior improvements to track the desired path of the robot manipulator. In the future work, the optimum suggested control method may be employed for more complicated (6–DOF) robot manipulator.

Conflict of Interest

The authors have declared no conflict of interest.

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