ELEKTROTEHNIŠKI VESTNIK 87(1-2): 53-59, 2020
ORIGINAL SCIENTIFIC PAPER

An Optimal PSO-Based Sliding-Mode Control Scheme for the Robot Manipulator

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Abstract. The paper investigates the possibility of optimizing the parameters of a nonlinear sliding-mode controller (SMC) used to control of a robot manipulator system. A new optimization method, dicly considering the effect of the SMC parameters on the performance robotic system, is proposed to optimize control parameters. Assuming the desired performance and elimination of the SMC application problem, i.e. the chattering phenomenon, a combination of the SMC and particle swarm optimization (PSO) algorithm to find the optimal parameters is proposed. Using a smooth function in SMC and PSO algorithm in searching for the optimal parameters provides a good solution. The performed numerical simulations of a two-link robot operation validate the effectiveness of the proposed control scheme.

Keywords: robot manipulator, PSO, nonlinear, sliding-mode control, optimization.

Optimizacija nelinearnega drsnega krmilnika za robotski manipulator

V prispevku obravnavamo optimizacijo parametrov pri nelinearnem drsnem krmilniku, ki ga uporabljamo za krmiljenje robotskega manipulatorja. Pri optimizaciji parametrov smo upoštevali, da so krmilni parametri v tesni povezavi z zmogljivostjo robotskega sistema. Predlagamo nov optimizacijski postopek za določitev krmilnih parametrov. Za dosego želene zmogljivosti in izločitev oscilacijskih motenj smo pri določitvi parametrov uporabili optimizacijo z rojem delcev. Pravilnost predlaganega postopka smo preverili z numerično simulacijo.

1 INTRODUCTION

The design of the robust adaptive controllers to control of multiple-input–multiple-output (MIMO) nonlinear systems is one of the most challenging tasks for many control engineers, especially when there is no complete knowledge of the system available. A robot manipulator is an uncertain nonlinear and coupled dynamic MIMO system that suffers from structured and unstructured uncertainties, such as payload variation, friction, external disturbances, etc. In the last few decades, many works associated with the theories of the classical and artificial intelligent control using many optimization algorithms have undergone a rapid development in the design of the feedback controller for complex systems.

To improve the performance of either, a conventional or intelligent controller, the controller parameters have to be optimized, especially when SMC is used, because of the existence of the chattering phenomenon which depends on the choice of the parameters. In the field of engineering, many optimization algorithms have been proposed. They are generally inspired by the nature and evolution. Such algorithms are the genetic algorithm (GA)[21], ant colony optimization, artificial bee colony, PSO and simulated annealing algorithm (SA). Judging from the literature and compared to other algorithms, PSO is the one that assures a better performance in terms of convergence towards a global optimum.

The PSO algorithm is a stochastic optimization method proving its efficiency through many reported studies, such as, nonlinear and non-differentiable problems, high-dimensional problems and control optimization [2][3].

The aim of our paper is to design a nonlinear SMC to improve the performance of the robot manipulator with no overshoot and to assure a good tracking of the desired trajectory in the presence of external disturbances. Using our PSO algorithm to determine the optimal controller parameters (gains) enables its desired performance. To build an objective function, such as the Integral Absolute Error (IAE), integral of the Squared Error (ISE), integral of the Time weighted Squared Error (ITSE) and Integral of the Time-weighted Absolute Error (ITAE), the literature offers a variety of functions.

Received 5 December 2018
Accepted 19 November 2019

2 DESCRIPTION OF THE ROBOT MANIPULATOR AND ITS STRUCTURAL PROPERTIES

The dynamics of an n-link robot manipulator can be described by a second-order nonlinear differential equation [15][16]

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + \tau_d = \Gamma \quad (1)$$

where $q, \dot{q}, \ddot{q} \in R^n$ are the link position, velocity, and acceleration vectors, respectively; Γ ⍰ $\in R^n$ is the vector of the applied link torques; $M(q) \in R^{n\times n}$ is the symmetric positive definite inertia matrix; $C(q,\dot{q})\dot{q} \in R^n$ is the Coriolis and centrifugal torque vector; $G(q) \in R^n$ is the gravity vector; and $\tau_d \in R^n$ is the vector of a generalized input disturbance.

The structural properties of each term in the robot dynamics equation (1) given in [9]. Provide on insight, to be used in deriving the robot control schemes [16] [9].

P1: $\emptyset_1 I_n \leq M(q) \leq \emptyset_2 I_n$ for some strictly positive constants $\emptyset_1$ and $\emptyset_2$ (2)

P2: $\dot{M}(q) - 2C(q,\dot{q})\dot{q}$ is a skew symmetric matrix. (3)

P3: $\|G(q)\| \leq g_{max}$ (4)

P4: $\|C(q,\dot{q})\| \leq \xi_c \|q\|$ where ξ_c is a positive constant (5)

Notice that $\|\quad\|$ denotes the Euclidean vector norm [9].

3 SLIDING-MODE CONTROLLER

SMC is a technique derived from the variable-structure theory. This controlling technique has the capacity to manage nonlinear and time-varying systems. In the nonlinear SMC design (Slotine et al.), for r=2 (the relative degree) of the proposed sliding surface s(t), the following equation [7][10] applies:

$$s(t) = \dot{e}(t) + \lambda\, e(t) \quad (6)$$

where s(t) is the n×1 vector, λ is the diagonal positive definite constant matrix that determines the slope of the sliding surface and $e(t) = q(t) - q_d(t)$ is the tracking position error in which $q_d(t)$ is the desired position trajectory and $\dot{e}(t) = \dot{q}(t) - \dot{q}_d(t)$ is the tracking velocity error in which $\dot{q}_d(t)$ is the desired speed trajectory.

Designing SMC enables the state vector *e(t)* to remain on the sliding surface (*s(t) = 0*) for all t ≥0. Therefore, the sliding surface needs to be attractive, i.e. $lim_{t\to\infty} e(t) = 0$; so that the error converges to zero asymptotically. This implies that the system dynamics tracks the desired trajectory asymptotically [19].

The derivative of the sliding surface is given by the following equation:

$$\dot{s}(t) = \ddot{e}(t) + \lambda\, \dot{e}(t) \quad (7)$$

Substituting (1) into (7) gives:

$$\dot{s}(t) = \ddot{q}(t) - \ddot{q}_d + \lambda\,(\dot{q}(t) - \dot{q}_d) \quad (8)$$
$$= M^{-1}(u - C.\dot{q}(t) - G) - \ddot{q}_d + \lambda\,(\dot{q}(t) - \dot{q}_d)$$

To achieve the desired performance, the solution of $\dot{s}(t) = 0$ determines the control effort to be applied. It is called the equivalent control and is designed as $u_{eq}(t)$:

$$u_{eq}(t) = C.\dot{q}(t) + G + M[\ddot{q}_d - \lambda\,(\dot{q}(t) - \dot{q}_d)] \quad (9)$$

However, at the occurrence of an unpredictable disturbance caused by a parameter variation or external-load disturbance, the equivalent control effort cannot ensure a favourable control performance. Hence, another control effort is added to eliminate the effect of an unpredictable disturbance. It is referred to as the control effort represented by $u_d(t)$, in [10]:

$$u_d(t) = -K\, sign(s(t)) \quad (10)$$

where $K = diag\{k_1, k_2, \dots, k_n\}$ is the control gain and $sign(.)$ is the sign function. For a two-DOF robot manipulator, n=2 and $K = diag\{k_1, k_2\}$.

In total, the SMC law for the nonlinearly uncertain systems to guarantee the stability and convergence can be represented as:

$$u(t) = u_{eq}(t) + u_d(t) = C.\dot{q}(t) + G + M[\ddot{q}_d - \lambda\,(\dot{q}(t) - \dot{q}_d)] - K\, sign(s(t)) \quad (11)$$

However, in a conventional SMC system, the sign function of the control law induces a chattering phenomenon in the control effort. That may excite unmodeled high-frequency modes, thus degrading the system performance and potentially leading to its instability. That is why many procedures have been designed to reduce or eliminate the chattering phenomenon. One of them is used in the control scheme in the vicinities of the switching surface. In its simplest case is replaced by a continuous approximation with a high gain in the boundary layer. Such functions are the sigmoid, saturation or tanh function. Another solution to cope with the chattering phenomenon is based on the theory of higher-order sliding modes [1] [19].

In our case, the sign function in the discontinuous controller is replaced by another function based on the tanh function.

4 PSO ALGORITHM

The PSO algorithm is a recent stochastic optimization method developed by Eberhart and. Kennedy in 1995 [5]. PSO is based on the social behaviour of animals, such as swarm of insects, school of fish or flock of birds [22]. The insects, fish, animals, especially birds, etc., always travel in a group of members by adjusting their positions and velocities to their group information. As this method reduces their individual effort for searching for the food, shelter, etc. [11]. In this algorithm, the population is termed the swarm and each its element the particle.

This evolutionary algorithm is used to optimize continuous or discrete, linear or nonlinear, constrained or unconstrained, non-differentiable functions by iteratively trying to improve the solutions for different parameter values.

The initialization of a 'swarm' is done with a population of random solutions. Each particle (k^{th} particle) has its position coordinates and its corresponding velocity is denoted respectively to $x_k = (x_{k1}, x_{k2}, \dots \dots x_{kN})$ and $v_k = (v_{k1}, v_{k2}, \dots \dots v_{kN})$ for the N-dimensional space.

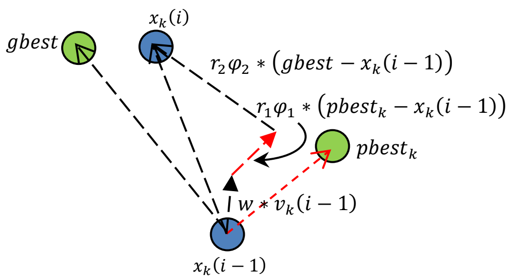

Figure 1. Schematic movement of a particle in PSO

During the optimisation process in which the previous information is used at each iteration, the algorithm updates the velocity and position of a particle shown in Fig. 1 [12] [24], according to the following equations:

$$v_k(i) = w * v_k(i-1) + r_1\varphi_1 * (pbest_k - x_k(i-1)) + r_2\varphi_2 * (gbest - x_k(i-1)) \quad (12)$$

$$x_k(i) = x_k(i-1) + v_k(i) \quad (13)$$

where w is the inertia weight, that controls the displacement impact on the future displacement; r_1 and r_2 are the random numbers between 0 and 1; and φ_1 and φ_2 are the acceleration constants used to control the cognitive behaviour and social aptitude of a particle, respectively. These two parameters are positives and are given in an empirical way according to the relation $\varphi_1 + \varphi_2 \leq 4$. During the optimization process, each particle also maintains a memory of its previous best position which is known as the personal best position and is denoted as pbest, and the global best position reached by a particle of a swarm is denoted as gbest [14][20].

The flow-chart of the PSO algorithm is given in Fig. 2.

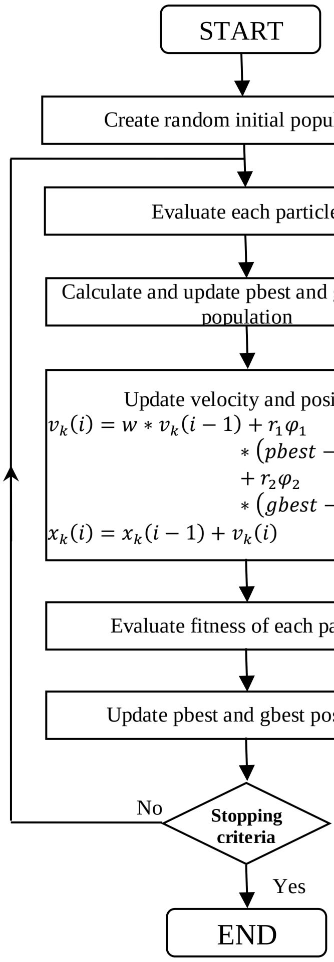

Figure 2. Flow-chart of the PSO algorithm

5 PSO-OPTIMIZED SMC

For the controllers described by Eqs. (6), (10) and (11), the following four parameters need to be specified: the λ_1 and λ_2 slope of the sliding surface and the k_1 and k_2 control gains. Using these parameters convergences the link positions to the desired positions. Unfortunately, there is no direct method to find these parameters because of the nonlinearities and the coupling effect of the robotic systems. PSO enables an optimal control by considering the performance and characteristics of the system observed and taking into account all the responses of the system to be adjusted, the wished dynamic performance for both links, minimal response time and establishment, static error zero, etc.

Fig 3 shows the structure of an optimized SMC process using the PSO algorithm.

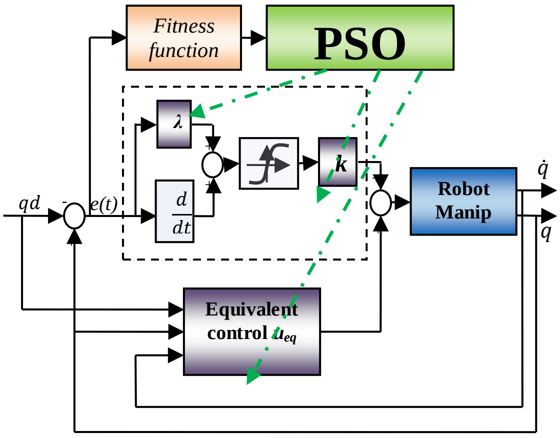

Figure 3. Proposed optimized control scheme.

The optimal SMC design problem is defined by determining k_1, k_2, λ_1 and λ_2 .
In the first step, the problem is encoded to construct the population in the PSO algorithm. All the controller parameters to be optimized present a possible solution to the problem.
The convergence towards the optimal SMC parameters follows the fitness function (either an objective or cost function). Hence, this error-based function must be correctly defined prior to the execution of the PSO algorithm. Our fitness function squared-error-based is given by the following equation:

$$fitness = \sum_{i=1}^{N} e(i)^2 = \sum_{i=1}^{N} error^2 \qquad (14)$$

where $e(i)$ is the trajectory error of the i^{th} sample and N is the sample number.

6 Simulation Results

The PSO algorithm-optimized controller given in section 3 is tested by two-degrees-of-freedom simulations of a rigid robot manipulator described in Fig. 4 and given by [8]:

$$M(q) = \begin{bmatrix} 8.77+1.02\cos(q_2) & 0.76+0.51\cos(q_2) \\ 0.76+0.51\cos(q_2) & 0.62 \end{bmatrix},$$

$$C(q,\dot{q}) = \begin{bmatrix} -0.5\sin(q_2)\dot{q}_2 & -0.5\sin(q_2)(\dot{q}_1+\dot{q}_2) \\ 0.5\sin(q_2)\dot{q}_1 & 0 \end{bmatrix} \text{ and}$$

$$G(q) = 10\begin{bmatrix} 7.6\sin(q_1)+0.63\sin(q_1+q_2) \\ 0.63\sin(q_1+q_2) \end{bmatrix}$$

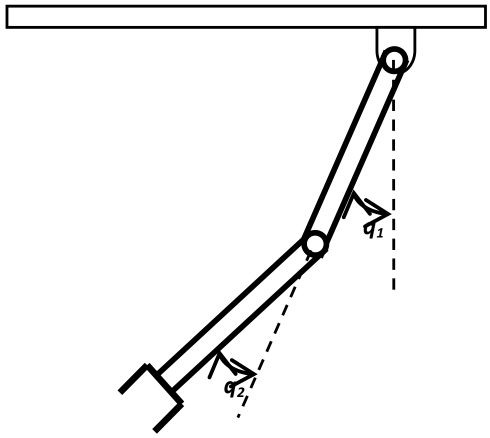

Figure 4. Two-degrees-of-freedom robot system.

6.1 PSO-based optimized SMC of the initial conditions of 0.1 and 0.2

The robot motion task is specified by defining the path along which a robot must move [23]. Several interpolation functions provide a trajectory such that $q(0) = q^{init}$ and $q(T) = q^{fin}$, where q^{init} and q^{fin} are the initial and final configuration, respectively. We choose the fifth-degree polynomial interpolation to ensure a smooth trajectory which is continuous in its positions, velocities and accelerations. The polynomial interpolation function is given by Khalil and all in [4].
To generate a trajectory, the desired values are $q_1^{fin} = 1.1\,rd$, $q_2^{fin} = 1.3\,rd$ and $q_1^{init} = q_2^{init} = 0\,rd$.

The values for the PSO parameters are given in Table 1.

Table 1. The PSO parameters for the SMC optimization

Parameter	Value
Cognitive constant (φ_1)	2
Group constant (φ_2)	2
Inertia weight (w)	1
Number of particles (n_p)	80
Number of iteration (n_{it})	150

The above parameters are determined through a series of experiments.
The best gain values obtained are shown in Table 2.

Table 2. The best gain values

k_1	k_2	λ_1	λ_2
504.2426	199.0399	19.0579	19.3883

Figs. 5 and 6 show the responses obtained for the two links of the same SMC for the tracking objective (Section 4). Figs. 7 and 8 show the links velocity, Fig. 9 the links position errors, and Fig. 10 the links control input of the initial conditions of 0.1 and 0.2.

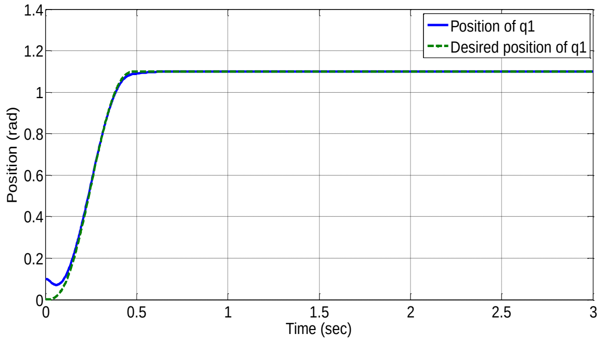

Figure 5. Position response of the first link angle (q_1).

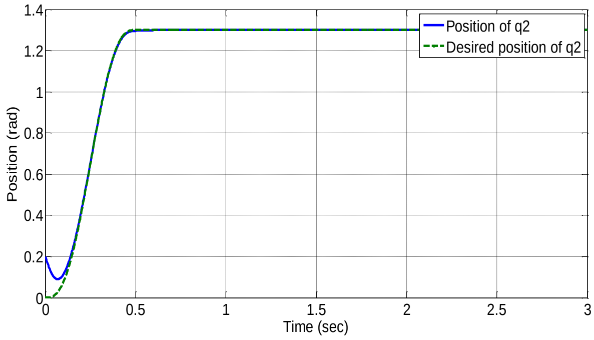

Figure 6. Position response of the second link angle (q_2).

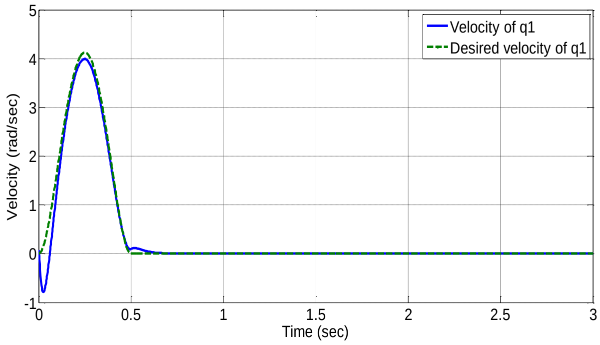

Figure 7. Angular velocity of the first link (q_1).

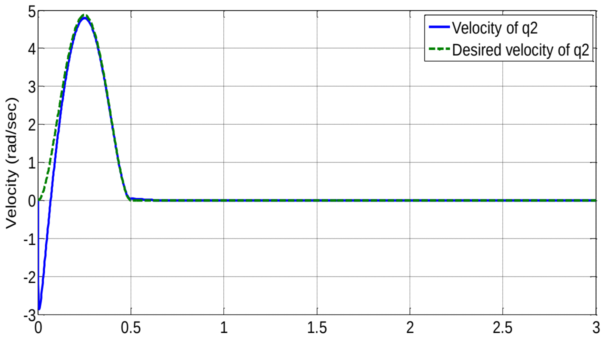

Figure 8. Angular velocity of the second link (q_2).

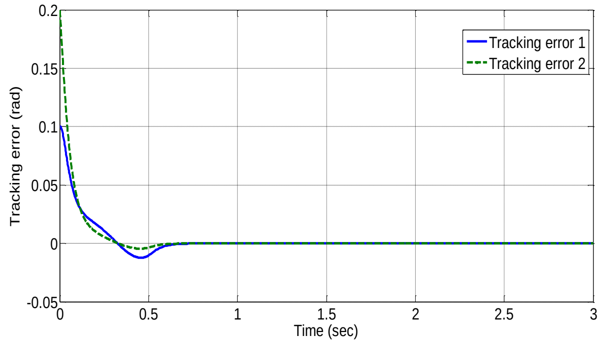

Figure 9. Tracking error of q_1 and q_2 .

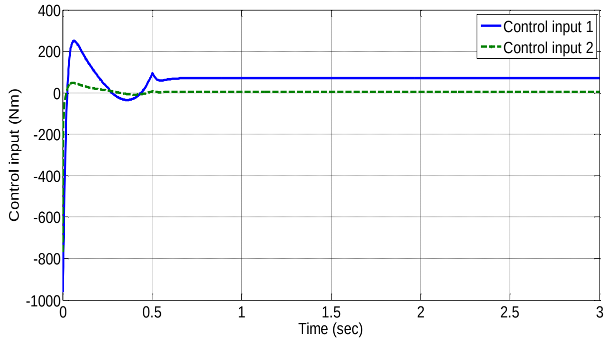

Figure 10. Control input for the two links.

6.2 At the initial conditions of -0.2 and -0.1

At this step, the same parameters are used. The initial conditions are changed to show the effectiveness of our SMC. The applied initial conditions are -0.1 and -0.2, the disturbance situation is created by injecting external forces into the robot system and using a uniformly distributed random shape as a disturbance signal.

Figs. 11 and 12 show the responses obtained of changed initial conditions for the two links. Figs. 13 and 14 show the velocity, and the Fig. 15 the position errors of the two links.

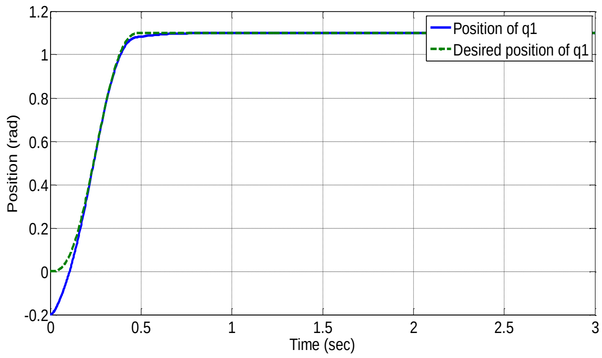

Figure 11. Position response of the first link angle (q_1) of the initial conditions of -0.2 and -0.1.

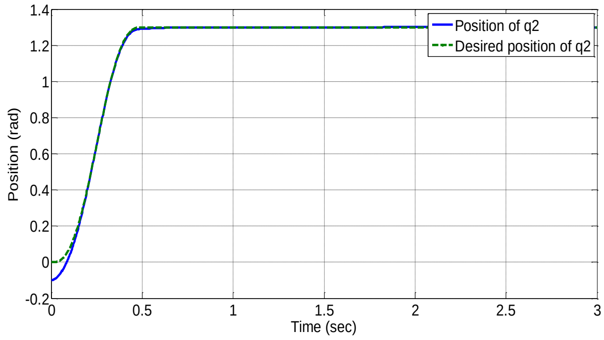

Figure 12. . Position response of the second link angle (q_2) of the initial conditions of -0.2 and -0.1.

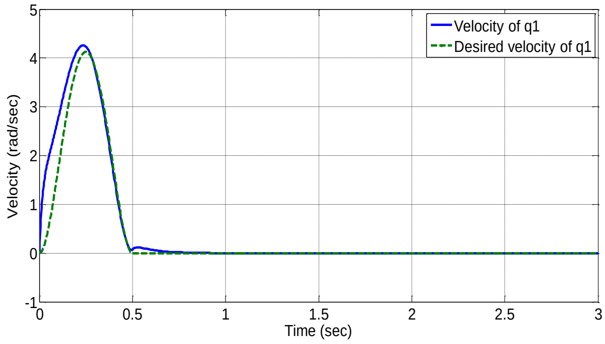

Figure 13. Angular velocity of the first link (q_1**)**.

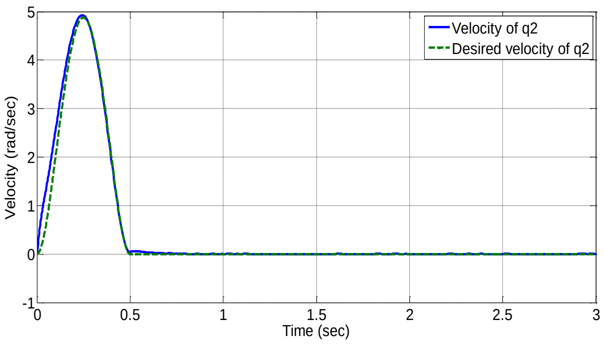

Figure 14. Angular velocity of the second link (q_2).

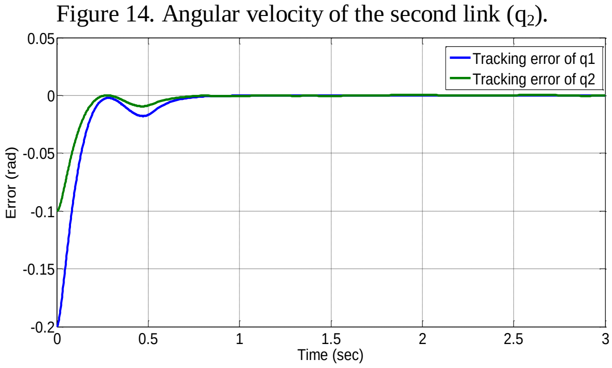

Figure 15. Tracking error of the first and second link (q_1 and q_2).

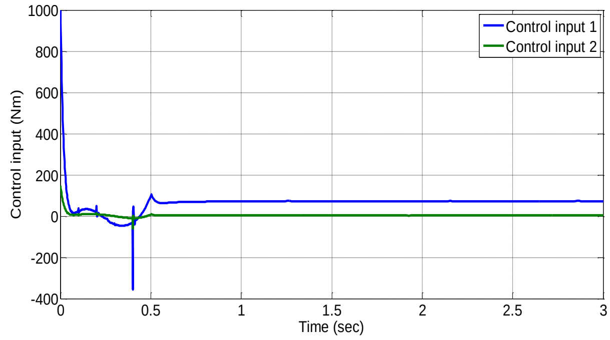

Figure 16. Control input for the two links.

Figs. 5-16 show that the PSO-optimized SMC provides a better control specification in terms of the fast response and trajectory tracking task and finds good parameters.

The results given in Figs. 5-10 are obtained by using the optimal control parameters of each link angle after 150 algorithm iterations, where the number of the particles used is 80. For the obtained parameters, the responses of the two links track the desired trajectories without overshooting though the initial conditions of the two links are not the initial points of the tracked trajectories and both errors converge to zero in a short period of time.

Fig. 11-16, show the results obtained by using the same optimal control of different initial conditions. To improve our algorithm they are changed to negative values for both links giving us a set of points on the other side of the origin of function, and the disturbance input is applied for both links. The results show that the obtained trajectory tracking is good and that the proposed controller rejects the disturbances.

7 Conclusion

An optimized nonlinear sliding-mode controller (SMC) is proposed for a two-link robot manipulator. The major problem when using SMC with a switching function is the chattering phenomenon. To eliminate its disturbing effect, the sign functions in the discontinuous control are substituted by a smooth function, such as the linear saturation boundary layer function or tanh function, whose structure, preserves the characteristics of the original functions. The SMC sliding surface is computed by using the generalized Slotine equation which reduces the complexity of the control scheme.

To simplify finding the optimal values of the SMC parameters, a Particle Swarm Optimization (PSO) algorithm is used. If identifies, the optimal gain and the best slope value of the sliding surface, within a given cost function. Compared to other optimization algorithms such as the Genetic algorithm, using the PSO algorithm gives a better quality. In our future work, several optimization methods will be compared to determine the optimal one.

To sum up, our simulation results confirm the good properties of the developed scheme, and the optimization approach proves to be effective in control applications.

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