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Firefly Algorithm Optimization of Manipulator Robotic Control Based on Fast Terminal Sliding Mode

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Abstract:
In this paper a new algorithm of optimization in the field of manipulator robotic control is presented. The proposed control approach is based on fast terminal sliding mode control (FTSMC), in order to guarantee the convergence of the position articulations errors to zero in finite time without chattering phenomena, and the Firefly algorithm in order to generate the optimal parameters that ensure minimum reaching time and mean square error and achieve better performances. This ensures the asymptotic stability of the system using a Lyapunov candidate in the presence of disturbances. The simulations are applied on a two-link robotic manipulator with different tracking references by using Matlab/ Simulink. Results show the efficiency and confirm the robustness of the proposed control strategy.

Keywords: *Manipulator robotic, fast terminal sliding mode, firefly algorithm, Lyapunov stability*

1. Introduction

The field of trajectory tracking control is one of the important researches on the manipulator robotics [1], [2]. Therefore, to improve the performance of robotic systems, several control approaches must be applied and implemented to obtain a robust and efficient control system.

To solve the problems of tracking control in this area, several researches are deployed: Such as PID tracking control [3], [4], computed torque control [5], adaptive control [6], [7], sliding mode control [8], [9], adaptive backstepping trajectory tracking [10], [11], fuzzy logic controller [12], neural network strategy [13].

Sliding mode control is one of the recent approaches which has shown its robustness against uncertainties and external disturbances [14], but conventional sliding mode control is known to incur chattering phenomena. Moreover, in order to eliminate this phenomenon, the sign function should be changed. However, the fast terminal sliding mode control displayed the problem of chattering, which guarantees the convergence of the errors in finite time.

In new researches on tracking control, a finite time tracking control was deployed [15][16]. A global finite-time tracking controller for manipulator robots based on inverse dynamics is presented in Su and Zheng [17]. For the differential equation of time analysis, the literature proposed finite time stability.

Optimization is a very important technique in the field of control where the control laws are based on gains and coefficients. The problem that arises, is how are these coefficients chosen? Then the main objective is to find the search process that maximizes or minimizes a cost function.

Recently, optimization techniques have attracted the attention of researchers who deal with the control problems of manipulator robotics. PSO-based PID and sliding mode control for manipulator robotics were implemented for optimizing and tuning the gains of PID, and improve the parameters of dynamic design in sliding mode control [18][19]. A combined genetic algorithm with sliding mode control with sliding perturbation provides the optimal gains in order to obtain the robust routine [20]. Another work used optimal sliding mode control based on a multi-objective genetic algorithm for manipulator robotic tracking control, which aims to not only minimize the chattering phenomenon but also increase performances of the system. This is presented in [21]. Sliding mode controller (SMC) with PID surface is introduced for the tracking control of a robot manipulator using Antlion optimization algorithm (ALO) and compared with another technique called gray wolf optimizer (GWO) [22]. A novel sliding mode (NSMC) which is combined with PID based on the extended grey wolf optimizer (EGWO) is applied on manipulator robot to optimize the control parameters (NSMC) [23].

In this paper a new meta-heuristic optimization method is introduced, namely, the firefly algorithm (FA) which is inspired by the real fire- flies' behavior. The firefly algorithm was developed in late 2007 and early 2008 by Xin-She Yang [24]. FA has been demonstrated to be very efficient in solving problems of global optimization, multimodal, and nonlinear problems.

This paper performs an optimal control on a two-link manipulator robot which is based on a new method of optimization in the field of tracking control of manipulator robotics by optimizing the objective function defined by Root Mean Square Error (RMSE). Based on the previous works using conventional sliding mode control, this paper aims to propose a fast terminal sliding mode control (FTSMC) avoids the chattering phenomenon and ensures the convergence of sliding surfaces in finite time, and also guarantees the stability of the system. For this purpose a combined firefly algorithm with FTSMC is suggested in order to demonstrate the efficient of the control strategy proposed.

The paper is organized as follows: Section 2 presents dynamic modeling of a two-link manipulator robot. The principal concepts of firefly algorithm are resumed in section 3. The control strategy based on FA-FTSMC is presented in section 4. The simulation and analysis of the improved control strategy are presented in Section 5. Finally, conclusions are drawn in Section 6.

2. Dynamic Modeling of Two-Link Manipulator Robot

Consider the two-link manipulator robot indicated in Figure 1. The robot has two junctions where the joint variables are defined by q_1 and q_2 as shown in the following figure:

The dynamic equation of the manipulator robot is given as follow:

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

Where $M(q)\in R^{2\times2}$ define positive is the inertia matrix. $C(q,\dot{q})\dot{q}\in R^{2\times2}$ is the matrix that represents the effects of centrifugal and coriolis, $G(q)\in R^{2\times1}$ is the gravitational vector, $\tau_d\in R^{2\times1}$ are the external disturbances and $\tau\in R^{2\times1}$ is the torque of the junctions, $q,\dot{q},\ddot{q}$ are angular position, velocity and acceleration of the junctions.

The matrices and vectors presented the dynamic equation are defined as follows:

$$M(q)=\begin{bmatrix} m_2a_2^2+2m_2a_1a_2\cos(q_2)+(m_1+m_2)a_1^2 & m_2a_2^2+m_2a_1a_2\cos(q_2) \\ m_2a_2^2+m_2a_1a_2\cos(q_2) & m_2a_2^2 \end{bmatrix}$$

$$C(q)=\begin{bmatrix} -2m_2a_1a_2\sin(q_2)\dot{q}_2 & -m_2a_1a_2\sin(q_2)\dot{q}_2 \\ m_2a_1a_2\sin(q_2)\dot{q}_1 & 0 \end{bmatrix}$$

$$G(q)=\begin{bmatrix} m_2a_2g\cos(q_1+q_2)+(m_1+m_2)a_1g\cos(q_1) \\ m_2a_2g\cos(q_1+q_2) \end{bmatrix}$$

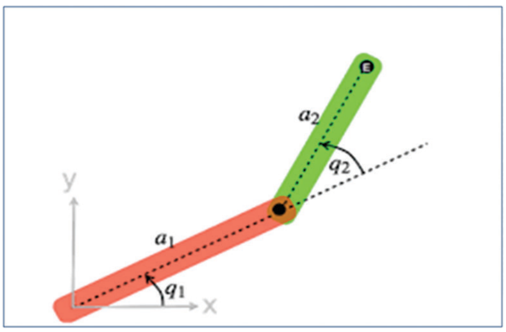

Fig. 1. Geometry of two-link manipulator robot

Where m_1, m_2 are the link masses, a_1 and a_2 are the link lengths, g is the gravitational acceleration.

3. Firefly Algorithm

Firefly algorithm (FA) was developed by Xin-She Yang in 2008 and in the last years it has become one of the important tools for solving the problems of optimization. FA attempts to imitate the flashing pattern and attraction behavior of fireflies. The purpose of these flashing lights is based on the following two points:

- Attract mating partners
- Warn potential predators.

Obviously, these indicators and their intensity are subject to physical laws. FA is based on the following three rules [24]:

1. Fireflies are unisex, so a firefly will be attracted to other fireflies, regardless of gender.
2. Attractiveness is proportional to luminosity, they decrease as their distance increases. So, for two flashing fireflies, the less bright will move to the brighter. If there is none brighter than a particular firefly, it will move randomly.
3. The brightness of a firefly is defined by the landscape of the objective function in order to obtain efficient optimal solutions.

The variation of attractiveness λ with the distance r can be defined by the following equation:

$$\lambda=\lambda_0e^{-\gamma r^2} \quad (2)$$

Where r is the distance between two fireflies, and Υ is the absorption parameter, λ_0 is the attractiveness at r=0.

The movement of a firefly i that is attracted to another more attractive (brighter) firefly j can be defined by the following equation:

$$X_i^{t+1}=X_i^t+\lambda_0e^{-\gamma r^2}(X_j^t-X_i^t)+\mu_t\varepsilon_i^t \quad (3)$$

The term $\lambda_0e^{-\gamma r^2}(X_j^t-X_i^t)$ represents the attraction, and the term $\mu_t\varepsilon_i^t$represents the randomization where μ is the randomization parameter, ε_i^t is a vector of random numbers obtain from a Gaussian distribution at time t, and Υ controls the scaling.

Randomness should be gradually lowered to ensure that the algorithm converges correctly, then to achieve this convergence one way is used:

$$\mu=\mu_0\theta^t,\theta\in(0,1) \quad (4)$$

Where μ_0 is the initial randomness factor, and t is the index of generations/ iterations.

The FA can be resumed in the following algorithm:

Begin algorithm

Initialize the parameters;
Define the objective function *f(X)*;
Generate the initial population of fireflies or X_i given in equation (3) where i=1,2,….n;
Define the light intensity of I_i at X_i with the function $f(X_i)$;
Determinate Y which is the light absorption;

Repeat

For *i=1* to *n*
For *j=1* to *n*
  If (I_j>I_i)
  Displace firefly *i* towards *j* ;
  Attractiveness varies with the distance *r;*
  End if
Evaluate new solutions and update light intensity;
End for *j*
End for *i*
Classify the fireflies and define the current best;

Until (t>MaxGeneration)
Postprocess results and visualisation;

End algorithm.

4. Control Strategy

In this work the control strategy is based on the fast terminal sliding mode controller, where the optimal parameters of the controller are delivered by the firefly algorithm in order to ensure a fast convergence and avoid the phenomenon of chattering, thus having a minimal MSE based on the objective function. Controller parameter must be considered as free parameters to be adjusted.

The objective of this strategy is to put the robot articulations following their references trajectory in presence of disturbances. The following figure resumes this control strategy.

From the figure, the control signal is presented by the torque vector $\tau = [\tau_1 \quad \tau_2]$, where the control laws are defined through the fast terminal sliding mode controller that it will be presented in the next section. Note that the articulation error is set to be an input for the controller as well as the optimized parameters *α, β, k, p, c*. The input signal is defined by the desired articulation variable $q_d = [q_{d1} \quad q_{d2}]$,

The control loop presented in Figure 2 will be repeated until reaching the number of iterations and optimal values of parameters are obtained.

4.1 Fast Terminal Sliding Mode Control

A new global fast terminal sliding surface proposed by Park et al [25] is given as follows:

$$S = \dot{s} + \alpha s + \beta s^{k/p} = 0 \tag{5}$$

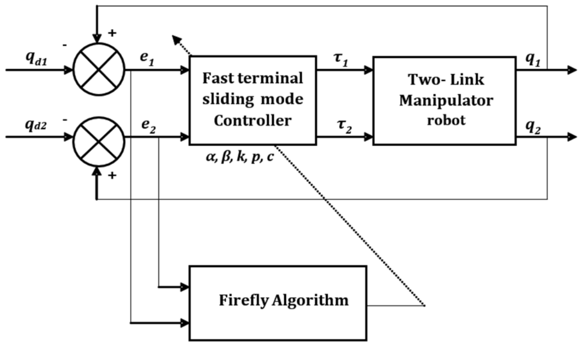

Fig. 2. Control strategy of manipulator robot

Where α, β > 0 and *k, p* (*k*<*p*) are positives odd numbers.

The reaching time of the sliding surface to zero is determinate as the following equation:

$$t_s = \frac{p}{\alpha(p-k)} \ln \frac{\alpha s(0)^{\frac{p-k}{p}} + \beta}{\beta} \tag{6}$$

In this work the sliding surface is based on the conventional sliding mode which is defined as follow:

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

Where *c* defined positive, *e* is the articulation error of the robot, and $\dot{e}$ is the derivative of the error which are defined as follow:

$$e = q - q_d \tag{8}$$

$$\dot{e} = \dot{q} - \dot{q}_d \tag{9}$$

And the second derivative of the articulation error is obtained as :

$$\ddot{e} = \ddot{q} - \ddot{q}_d \tag{10}$$

The error signal of tracking is defined in what follow:

$$\dot{q}_r = \dot{q}_d - ce \tag{11}$$

By replacing equation (11) in (7), the equation (7) can be rewritten as follow:

$$s = \dot{q} - \dot{q}_d + ce = \dot{q} - \dot{q}_r \tag{12}$$

The derivative of sliding surface can be obtained as:

$$\dot{s} = \ddot{q} - \ddot{q}_r \tag{13}$$

To obtain the control low, we start from the equation (13), so this last is multiplied by the inertia matrix *M(q)*, and according to equation (1) the control law can be given as follow:

$$\tau = M(q)\dot{s} + C(q,\dot{q})\dot{q} + G(q) + M(q)\ddot{q}_r \tag{14}$$

According to equation (5):

$$\dot{s} = -\alpha s - \beta s^{k/p} \tag{15}$$

Replacing (15) in (14), the control low becomes:

$$\tau = M(q)(-\alpha s - \beta s^{k/p}) + C(q,\dot{q})\dot{q} + G(q) + M(q)\ddot{q}_r \tag{16}$$

Proof: to ensure the stability of the system, the Lyapunov candidate is choosing as:

$$v = \frac{1}{2} s s^T \tag{17}$$

The derivative of this equation is obtained as the following steps:

$$\dot{v} = s^T \dot{s} = s^T (\ddot{q} - \ddot{q}_r) \tag{18}$$

With

$$\ddot{q} = M^{-1}(q)(\tau - C(q,\dot{q})\dot{q} - G(q)) \tag{19}$$

According to equations (19) and (16), equation (18) can be rewritten as:

$$\dot{v} = s^T (M^{-1}(q)(\tau - C(q,\dot{q})\dot{q} - G(q)) - \ddot{q}_r))$$

$$= s^T(-\alpha s - \beta s^{k/p}) \tag{20}$$

Such that α, β, k, p are defined positive, therefore $\dot{v}$ is negative definite.

4.2 Objective Function Definition

The main objective of the proposed FA-FTSM controller is to tune optimally as fast as possible the FTSM controller parameters by minimization of the objective function, which can be formed by different performances specification such as the root mean square error (RMSE). In this paper the objective function is defined as the MSE error which can be given as follow:

$$f(X) = \frac{1}{N}\sum_{i=1}^{N}\sqrt{e_1^{\,2}(i) + e_2^{\,2}(i)} \tag{21}$$

where $X = [\alpha, \beta, k, p, c]$ is a parameter set of FTSM controller and N is the number of data samples, e_1 and e_2 are the tracking articulation errors.

According to the FA, the optimizer will define the unknown FTSMC free parameters by updating the solutions based on the objective function.

5. Results and Discussion

In this section MATLAB/SIMULINK is choosing in order to simulate the proposed method of control, and to verify its effectiveness. So we evaluate through computer simulation, the ability of the proposed FTSM controller to deal with the controller tuning and permit to the manipulator follow the trajectory generated by the input signal which is the desired articulation variables. However the optimization performances are evaluated using the RMSE criterion.

In these simulations a two-link manipulator robot shown in Figure 1 is considered. The dynamic equation of this two-link robot is given in equation 1.

Let us consider a sinusoidal desired position commands of two articulations are given as $q_d = [0.1\sin(t) \quad 0.1\sin(t)]$, the disturbance is selecting as $\tau_d = [0.2\sin(t) \quad 0.2\sin(t)]$, and for simulation purposes parameters of the robot are taken as:

m1=m2=0.5Kg, a1=a2=1m, and g=9/8 m/s2.

The FA parameters values are resumed in Table 1:

In the first step of simulations an offline optimization is considered in order to define the upper bound and lower bound of each control parameter (α, β, k, p) with different criteria of the proposed optimization algorithm. Note that the objective function in this step is considered as the reaching time of the sliding surface giving in equation (6). Therefore, the objective of proposed work is to minimize the reaching time and obtain the minimum MSE with optimal solutions. The fact that the parameters are defined we introduce them in the control loop strategy given in Figure 2, when the objective function is given in equation (21).

Figure 3 shows the iteration of firefly algorithm with mean square error and objective function, where the RMSE decreases until it reaches the optimal value for parameters, with best fitness= 1.5665e-04; which prove the performance of the optimization process.

Hence, in Figure 4 the position tracking of two joints is shown, where the proposed controller shows good tracking and rapidly convergence towards the proposed reference joint positions.

Moreover, in the Figure 5 the joint velocities can attain their reference velocities in finite time. Figure 6 represents the control input torques which can guarantee the convergence of the tracking joint errors to zero and assure the stability of the system in presence of disturbances. The results shown in previous figures confirm the effectiveness and robustness of the proposed method, also the fast convergence.

In Table 2, the optimal value of RMSE which corresponds to the best estimate parameters of the proposed controller are defined.

In the next step of simulation, a conventional sliding mode controller tuned by the firefly algorithm

Tab. 1. Parameters values of firefly algorithm

Parameter	Designation	Value
n	Number of fireflies	50
μ_0	Randomness	0.2
λ	Initial attractiveness	2
Υ	Absorption coefficient	1
ng	Number of generation	60

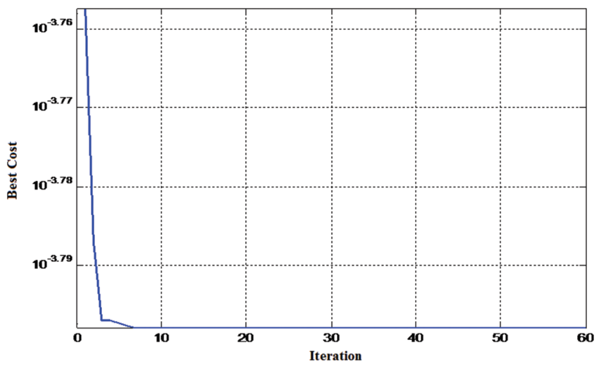

Fig. 3. Objective function evolution

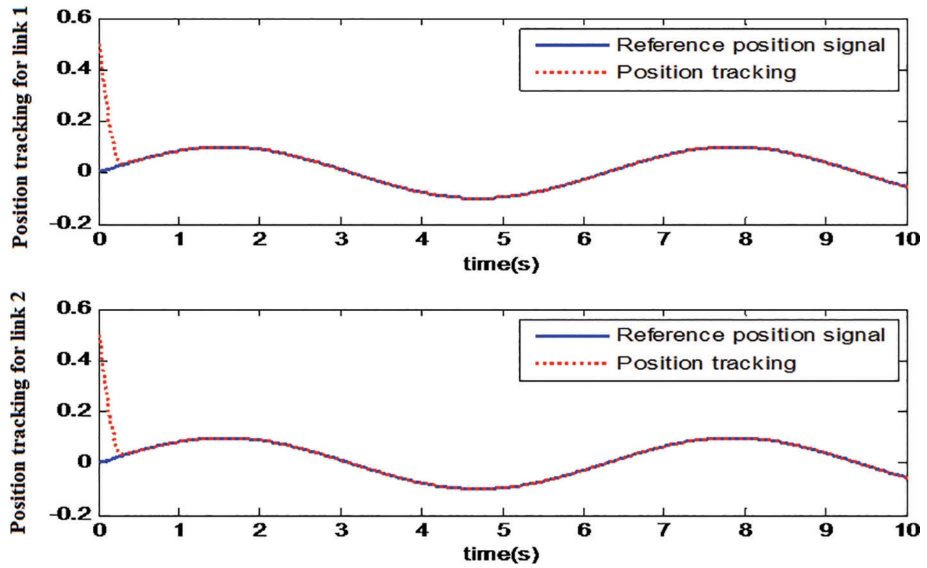

Fig. 4. Position tracking of joints 1 and 2

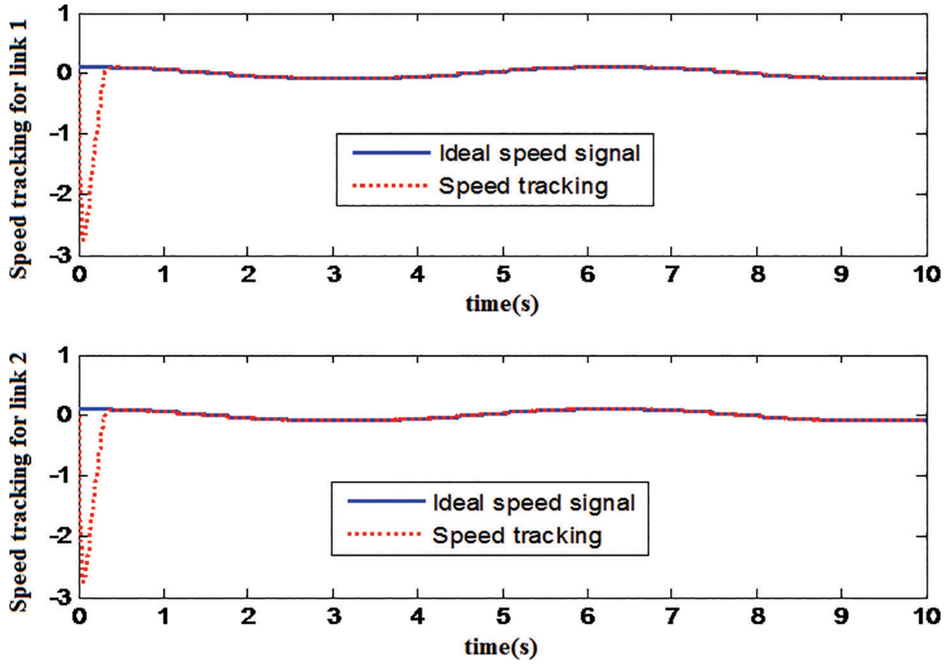

Fig. 5. Velocity tracking of joints 1 and 2

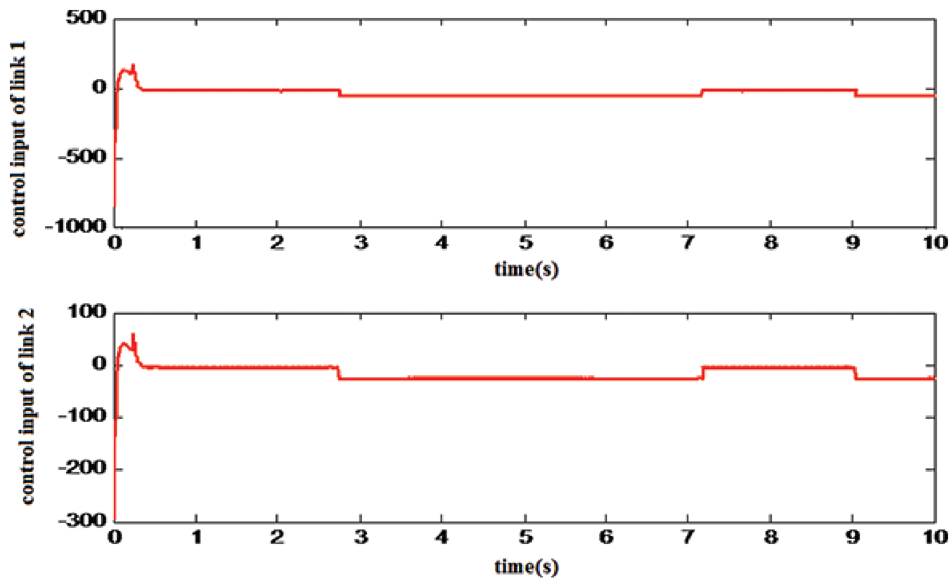

Fig. 6. Control inputs of joints 1 and 2

(FA-CSMC) is introduced to validate the proposed approach in robustness and stability; a comparative study is presented in order to compare the proposed approaches. Therefore, in this case the control law given in equation (16) can rewrite as follow:

$$\tau = C(q,\dot{q})\dot{q} + G(q) + M(q)\ddot{q}_r - cM(q)sign(s) \quad (21)$$

Tab. 2. Simulation results using FA-FTSMC

Results	Number of fireflies n=25	Number of fireflies n=50
MSE	1.5921e-04	1.5665e-04
α	8.4480	7.631
β	20.00	20.00
k	0.1000	0.500
p	2.7033	10.00
c	30.00	29.5262

The results obtained presented in Figure 7 and Figure 8 show good tracking and convergence towards the proposed reference joint positions. Figure 9. represents the control input torques, in which the chattering phenomenon is appeared. It can be noticed that the control input torque response in the case of FA-FTSMC is more stable, and the chattering is eliminated.

Table 3 resume the comparative study of the approaches presented, when the comparing criteria was done by using Mean Square Error (MSE) and reaching time (t_s) defined in equation (6).

Based on the comparative study given in Table 3, we confirm that the FA-FTSMC approach ensure more effectiveness and robustness than other proposed approaches in term of fast convergence and in term of less RMSE.

The results obtained shown in Figure 10 and Figure 11 confirm the efficiency of FA-FTSMC addressed in Table 3.

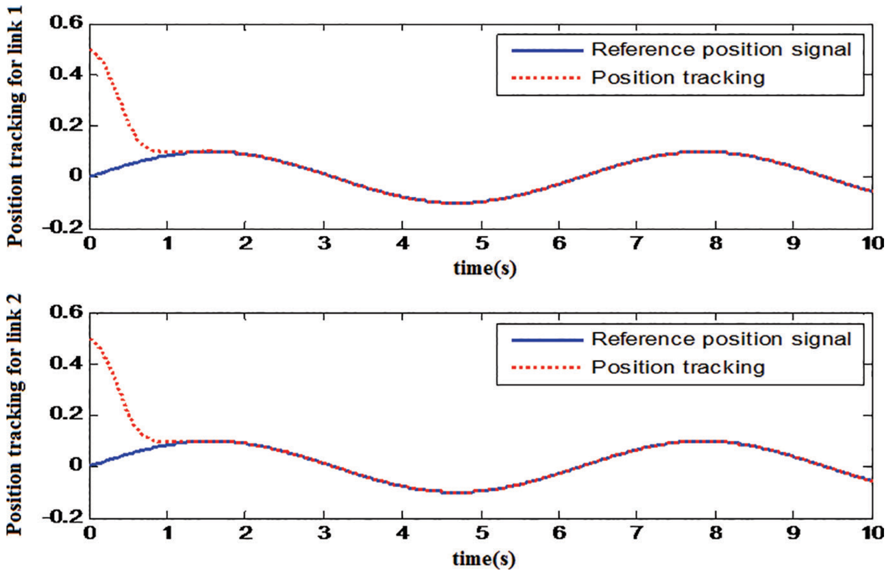

Fig. 7. Position tracking of joints 1 and 2(FA-CSMC)

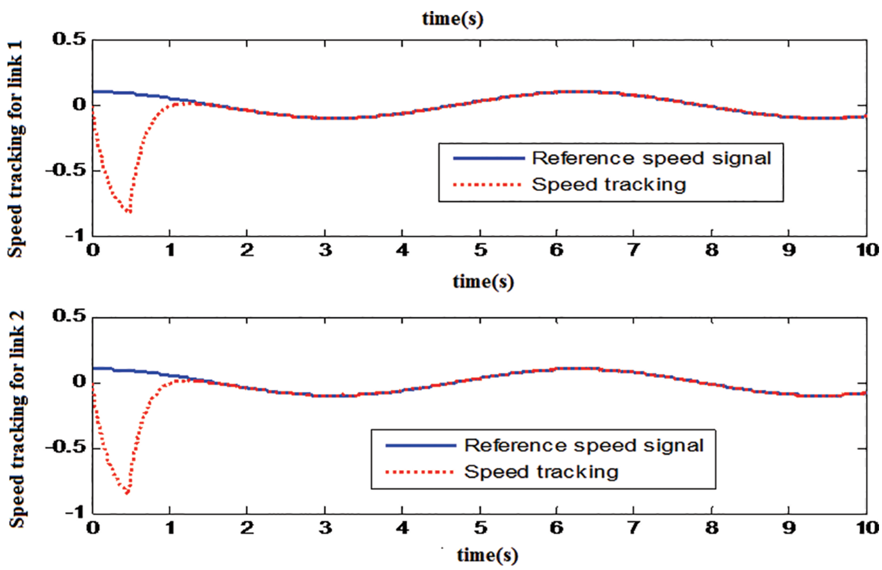

Fig. 8. Velocity tracking of joints 1 and 2(FA-CSMC)

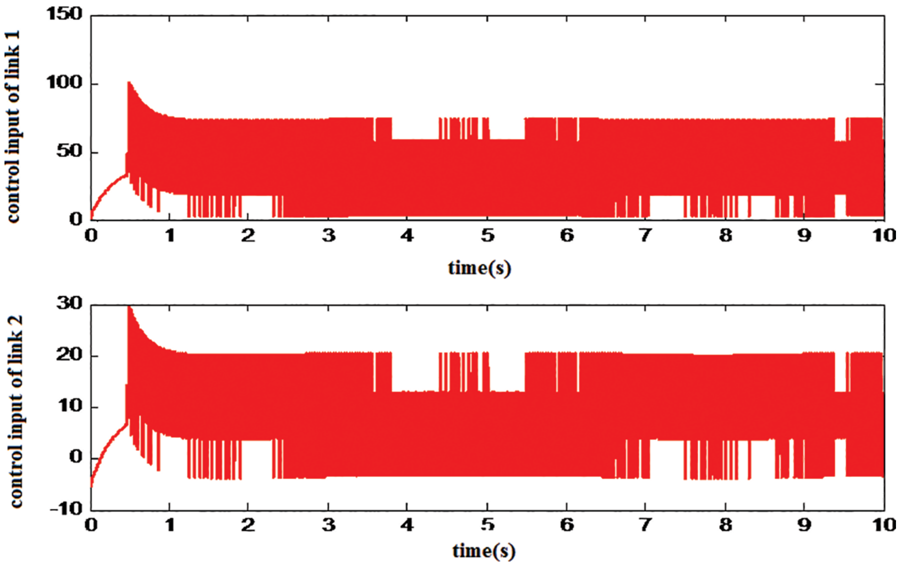

Fig. 9. Control inputs of joints 1 and 2(FA-CSMC)

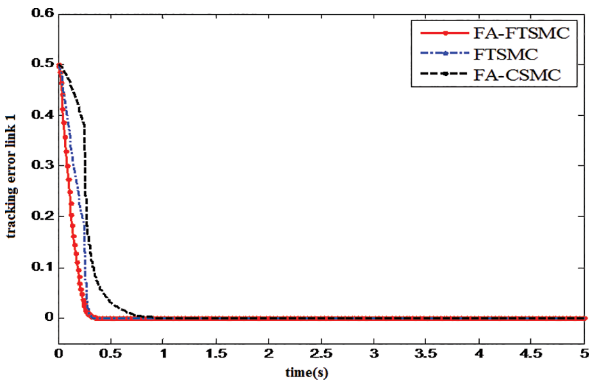

Fig. 10. Tracking errors of joint 1

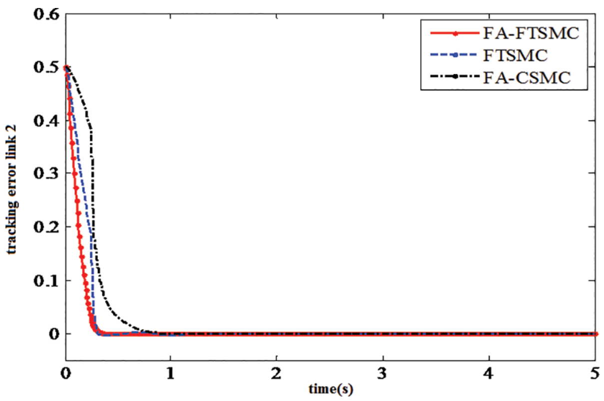

Fig. 11. Tracking errors of joint 2

Tab. 3. Comparative study between the proposed approaches

Results	FTSMC	FA-FTSMC	FA-CSMC
RMSE	0.0020	1.5665e-04	2.448 e-04
Reaching time(ts)	0.6065	0.0533	0.6931
α	4	7.631	/
β	2	20.00	/
k	5	0.500	/
p	7	10.00	/
c	20	29.5262	25.38

6. Conclusion

In this paper a FA-FTSM control is proposed to ensure the optimal tracking of two-link manipulator robot, taking into account the dynamics of the robot. The proposed controller demonstrate that it can be make the system converges to the reference in a finite time without chattering phenomena even in presence of disturbances.

Firefly algorithm is introduced in this paper for tuning the FTSM controller parameters in order to obtain the less RMSE and reaching time which permit a fast convergence. The obtained simulations results show that the proposed approach perform an efficient search for the optimal FTSM controller parameters.

Simulations results have demonstrated the robustness and the effectiveness of the approach proposed where it was confirmed by a comparative study with a combined firefly algorithm and conventional sliding mode (CSM), in which it proved that the optimization in the FA-FTSM case is faster than FA-CSM.

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