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New Sliding Mode Control of 2-DOF Robot Manipulator Based on Extended Grey Wolf Optimizer

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Abstract: This paper presents a novel sliding mode (NSMC) to control of a 2-DOF robot manipulator based on the extended grey wolf optimizer (EGWO). The PD control approach is not robust against external disturbances compared to the sliding mode control (SMC) method, but SMC is noticeably robust against uncertainties and external disturbances. By using both PD and SMC, a novel control approach is proposed to remove each of the controller's disadvantages. In this paper, the grey wolf optimizer (GWO) is extended to EGWO algorithm by adding the emphasis coefficients. The GWO, and EGWO then are applied to optimize the proposed control parameters (NSMC-EGWO) which result the optimized NSMC-GWO, and NSMC-EGWO respectively. The stability of the NSMC is proved by Lyapunov theory. The performance of the proposed control method is compared with two other controllers such as SMC and proportional derivative sliding mode control (PDSMC). Numerical simulations completely verified the effectiveness of the proposed control approach.

Keywords: Grey wolf optimizer, hybrid control, robot manipulator, sliding mode control.

1. INTRODUCTION

Robot manipulators have been widely used in industrial structures. In order to improve their performances, a convenient control method should be applied. Many controller methods have been implemented to these systems to achieve a precise, robust and effective control system. Jin *et al*. [1] proposed a practical nonsingular terminal sliding mode control approach for robot manipulators using time-delay estimation. The proposed control guarantees fast convergence because of the nonlinear terminal sliding mode, and requires no prior knowledge about the robot dynamics due to the time-delay estimation. Efe [2] proposed a new parameter adjustment approach to enhance the robustness of fuzzy sliding mode control obtained by the use of an adaptive neuro-fuzzy inference system structure. The proposed method uses fractional-order integration in the parameter tuning stage. It was seen that the control system with the proposed adaptation method clearly demonstrates better tracking performance, and high degree of robustness and insensitivity to external disturbances. Wan *et al*. [3] proposed the force/position hybrid control method for 6 PUS-UPU redundant actuation parallel robot. Also, the proportional integral and model predictive control cascade control strategy are utilized in the redundant branch of 6 PUS-UPU. The simulation results illustrate that the model predictive control can significantly improve the tracking ability of the system. Rahmani *et al*. [4] proposed a control method based on the fraction integral terminal sliding mode control and adaptive neural network. It deals with the system model uncertainties and the disturbances to improve the control performance of the Inchworm robot manipulator. A fraction integral terminal sliding mode control uses to the Inchworm robot manipulator to obtain the initial stability. Also, Rahmani and Ghanbari [5] utilized a neural computed torque controller for Caterpillar robot manipulator control. The discovered figures show that the performance of neural computed torque controller is better than a conventional computed torque controller in trajectory tracking. Capisani *et al*. [6] to handle the model uncertainties and external disturbances affecting the robot, the inverse dynamic controller combined with a method based on higher-order sliding mode controller.

A higher-order SMC scheme transfers the inherent discontinuous profile for the input torque, which is computed through integration of a convenient discontinuous switching signal. Islam *et al*. [7] proposed the single-mode based SMC method in order to cope with large-scale parametric uncertainties. Asl *et al*. [8] proposed a

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novel control law along with an unscented Kalman Filter based on the non-singular terminal sliding mode control for robotic manipulator. This control method expected to tolerate external disturbances and noises with unknown statistics. Ma *et al*. [9] proposed a dual terminal sliding mode control method for tracking of rigid robotic manipulators. The proposed approach can simply combine with adaptive techniques to eliminate the problems caused by the input limitation in the rigorous stability analysis. Achili *et al*. [10] proposed an adaptive observer based on a Multi-layer perceptron neural network (MLPNN) and a SMC technique. The MLPNN selected for its feature of universal approximation has been utilized to identify the unknown dynamic. The proposed research has been verified in both simulation and experimentation. Kumar *et al*. [11] proposed a new application of a genetic algorithm optimization method to optimize the scaling factors of interval type-2 fuzzy PD plus integral controllers for 5-DOF redundant robot manipulators for trajectory tracking tasks. The experimental application showed that the proposed controller cannot only guarantee the best trajectory tracking in joint and Cartesian space, but also improve the robustness of the systems random noise, parameter variations, and external disturbances. Ouyang *et al*. [12] proposed a novel model-free control law, called PD with SMC approach for trajectory tracking control of multi-degree-of-freedom linear translational robotic systems. The novel control method takes the advantages of the simplicity and easy design of PD control and the robustness of SMC to model uncertainty and parameter fluctuation, and avoid the requirements for recognized knowledge of the system dynamics related to SMC. Simulation results prove the effectiveness and robustness of the proposed control law. Also, myriad control systems have been used in order to improve robot manipulators' trajectory tracking [13–19].

The Grey wolf optimizer (GWO) algorithm firstly has been introduced by Mirjalali *et al*. in 2014 [20] which shows pioneering results in optimizing problems [21]. This algorithm is a meta-heuristic optimizing system mimics the group of grey wolves (Alpha, Beta, Delta, and Omega) hunting approach (including searching for a prey, surrounding the prey, and attacking) in nature. GWO is used to minimize the power losses in the power distribution network in [22], for optimizing the fitness function for a fuzzy system in order to use in image segmentation in [23], to calculate the optimal parameters of a degradation trajectory utilizing the features of a weighted fusion function in [24]. To control a quadruped robot, an optimized PID control is proposed. GWO is used to tune the PID controller parameters to obtain the desired trajectory. The performance of the proposed GWO is compared with some other optimization algorithms such as Genetic Algorithm and Particle Swarm Optimization. Simulation results clearly verified that the GWO has better performance in comparison with two other applied algorithms [25]. In order to control a two-wheeled inverted pendulum, a fractional order PID controller proposed. The GWO is used to tune the fractional order PID controller parameters [26].

This paper proposes a novel control approach to improve tracking performance. A new sliding surface is applied in order to enhance the robustness of the control system. Next, EGWO is applied in order to tune the proposed controller parameters. Furthermore, the proposed control method compared with SMC and PDSMC.

The rest of this paper arranged as follows: In Section 2, the dynamic modeling of a 2-DOF robotic manipulator is described. In Section 3, PDSMC has been delineated. In Section 4, the implementation of NSMC is described. Section 5 described EGWO. Section 6 presents the simulation results. Finally, supply the conclusion and contributions of the work.

2. DYNAMIC MODELING OF A 2-DOF ROBOT MANIPULATOR

Fig. 1 shows the schematic of a 2-DOF robot manipulator. The dynamic modeling of a 2-DOF robot manipulator can be expressed as follows [1]:

$$B(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)=\tau, \tag{1}$$

where q, $\dot{q}$, $\ddot{q}\in R^2$ represent the position, velocity, and acceleration of the joints, respectively, and $B(q)\in R^{2\times 2}$ known as the generalized inertia matrix, $C(q,\dot{q})\in R^{2\times 2}$ is the vector of Coriolis and centrifugal forces, $G(q)\in R^2$ the gravitational vector, and $\tau\in R^2$ the joint torques. $B(q)$, $C(q,\dot{q})$ and $G(q)$ are given in Appendix A. Equation (1) can be written as:

$$\begin{aligned}\ddot{q}=&-B^{-1}(q)C(q,\dot{q})\dot{q}-B^{-1}(q)G(q)\\&+B^{-1}(q)\tau.\end{aligned} \tag{2}$$

The dynamic equation for a 2-DOF robot manipulator can be re-arranged as:

$$\ddot{q}=-M\dot{q}-NG(q)+Ou, \tag{3}$$

where $M=B^{-1}(q)C(q,\dot{q})$, $N=B^{-1}(q)$, $O=B^{-1}(q)$, $u(t)=\tau$ is the control vector. ΔM, ΔN, and ΔO present

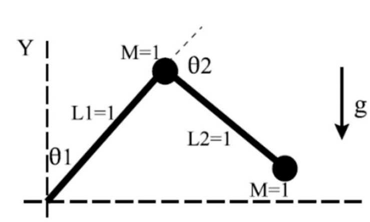

Fig. 1. Structure of a 2 DOF robot manipulator.

some uncertainties of parameter variations. Therefore, (3) can be defined as:

$$\begin{aligned}\ddot{q} =& -(M+\Delta M)\dot{q}-(N+\Delta N)G(q)\\ &+(O+\Delta O)u(t).\end{aligned} \tag{4}$$

Equation (4) can be rewritten as:

$$\ddot{q} = -M\dot{q}-NG(q)+Ou(t)+d(t). \tag{5}$$

where $d(t) = -\Delta M\dot{q}-\Delta NG(q)+\Delta Ou(t)$.

3. PD SLIDING MODE CONTROL

The PDSMC approach can guarantee that the states converge to the origin in finite time, achieving a better tracking performance and a faster convergence. However, the PD sliding mode surface is selected due to the high tracking performance that PD controller has in comparison with PID controller. PDSMC surface can be defined as follows:

$$s(t) = k_p e(t) + k_d \frac{d}{dt}e(t), \tag{6}$$

where k_p is 2×2 positive proportional gain matrix, and k_d is 2×2 positive derivative gain matrix parameters to be chosen for 2-DOF robot manipulator. The purpose of the SMC method is to force tracking error to approach the sliding surface and then move along the sliding surface to the origin.

Thus, in order to the error die out asymptotically, it is required that the sliding surface be stable, which means $\lim_{x\to\infty} e(t) = 0$. Take the derivative of PD sliding mode surface with respect to time produces:

$$\begin{aligned}\dot{s}(t) =& k_p\dot{e}(t)+k_d\ddot{e}(t)\\ =& k_p\dot{e}+k_d[-M\dot{q}-NG(q)+Ou(t)+d(t)-\ddot{q}_d].\end{aligned} \tag{7}$$

The control effort being derived as [27]:

$$\begin{aligned}u_{eq}(t) =& (k_dO)^{-1}[-k_p\dot{e}(t)+k_dM\dot{q}\\ &+k_dNG+k_d\ddot{q}_d-k_dd(t)].\end{aligned} \tag{8}$$

However, the equivalent control effort cannot guarantee favorable control performance if unpredictable perturbations from the parameter variations or external load disturbance occur [27]. The auxiliary control effort is referred to as reaching control effort represented by $u_s(t)$.

A sufficient condition to ensure that the trajectory of the tracking position error will translate from reaching phase to sliding phase is to choose the control approach. Also, it can be defined as the reaching condition [28–30]:

$$\dot{V}(t) = s^T(t)\dot{s}(t) < 0, \quad s(t)\neq 0. \tag{9}$$

The equivalent control $u_{eq}(t)$ given in (7) is augmented by a hitting control term $u_s(t)$ in order to satisfy the reaching condition. The SMC law can be shown as follows:

$$u(t) = u_{eq}(t)+u_s(t). \tag{10}$$

To obtain the reaching control signal $u_s(t)$, (9) is denoted as:

$$\begin{aligned}s^T\dot{s} =& s^T(k_p\dot{e}+k_d\ddot{e}) = s^T(k_p\dot{e}+k_d(\ddot{q}-\ddot{q}_d))\\ =& s^T[k_p\dot{e}+k_d(-M\dot{q}-NG+O(u_{eq}(t)\\ &+u_s(t))-\ddot{q}_d+d(t))]\\ =& s^T[k_p\dot{e}-k_dM\dot{q}-k_dNG+k_dOu_{eq}(t)\\ &+k_dOu_s(t)-k_d\ddot{q}_d+k_dd(t))].\end{aligned} \tag{11}$$

Substitute (8) into (11) generates

$$s^T\dot{s} = s^T[+k_dOu_s(t)] \le s^T[+k_d|O|u_s(t)]. \tag{12}$$

To ensure (12) is less than zero, the reaching control law should be chosen as:

$$u_s(t) = K_s sign(s(t)). \tag{13}$$

Clearly, substituting (13) into (12) we can find that our controller is stable, where $K_s = diag\{K_{s1}, K_{s2}, \ldots, K_{sm}\}$ represents reaching control gain respect to the upper bound of uncertainties.

4. NEW ROBUST SLIDING MODE CONTROL

In order to increase the efficiency of the control performance in trajectory tracking, a new sliding mode surface is required, which can be defined as follows:

$$s(t) = k_p e(t) + k_d\frac{d}{dt}e(t)+\gamma e^{\mu}, \tag{14}$$

where γ and μ are positive parameters to be chosen for a 2-DOF robot manipulator. The purpose of SMC method is to force tracking error to approach the sliding surface and then move along the sliding surface to the origin.

Therefore, it is required that sliding surface be stable, which means in order to the error die out asymptotically, take the drivative of the proposed control method with respect to time, then

$$\begin{aligned}\dot{s}(t) =& k_p\dot{e}(t)+k_d\ddot{e}(t)+\gamma\mu\dot{e}e^{\mu-1}\\ =& k_p\dot{e}+\gamma\mu\dot{e}e^{\mu-1}\\ &+k_d[-M\dot{q}-NG(q)+Ou(t)+d(t)-\ddot{q}_d].\end{aligned} \tag{15}$$

The equivalent control can be obtained as:

$$\begin{aligned}u_{eq}(t) =& (k_dO)^{-1}[-k_p\dot{e}(t)-\gamma\mu\dot{e}e^{\mu-1}\\ &+k_dM\dot{q}+k_dNG+k_d\ddot{q}_d-k_dd(t)].\end{aligned} \tag{16}$$

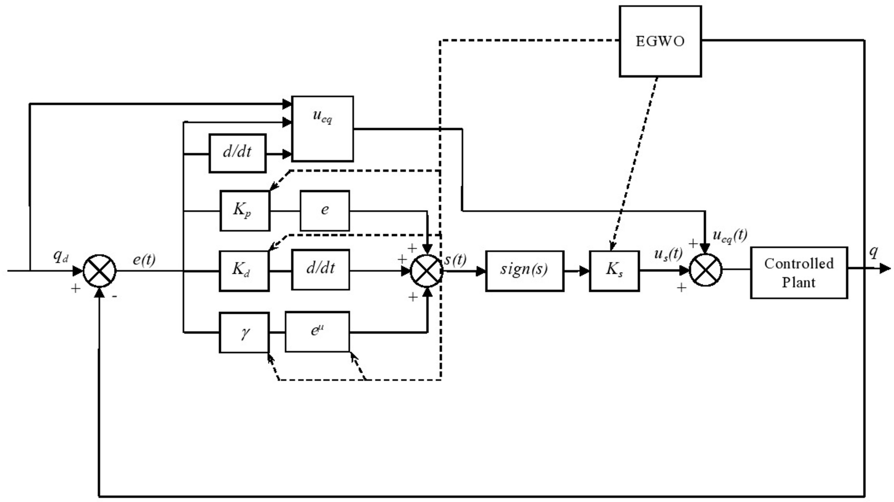

Fig. 2. Block diagram of the proposed control method.

However, the equivalent control effort cannot guarantee favorable control performance if unpredictable perturbations from the parameter variations or external load disturbance occur. The auxiliary control effort is referred to as reaching control effort represented by $u_s(t)$. For this task, the Lyapunov function can be defined as follows [31–36]:

$$V(t) = \frac{1}{2}s^T(t)s(t), \tag{17}$$

with $V(0) = 0$ and $V(t) > 0$ for $s(t) \neq 0$. A sufficient condition to ensure that the trajectory of the tracking position error will translate from reaching phase to sliding phase is to choose the control approach. Also, it can be defined as the reaching condition:

$$\dot{V}(t) = s^T(t)\dot{s}(t) < 0, \quad s(t) \neq 0. \tag{18}$$

The equivalent control $u_{eq}(t)$ given in (16) is augmented by a hitting control term $u_s(t)$ in order to satisfy the reaching condition. The proposed control method is illustrated in Fig. 2. The SMC law can be shown as follows:

$$u(t) = u_{eq}(t) + u_s(t). \tag{19}$$

To obtain the reaching control signal $u_s(t)$, (18) is denoted as:

$$\begin{aligned} s^T\dot{s} =& s^T(k_p\dot{e} + k_d\ddot{e} + \gamma\mu\dot{e}e^{\mu-1}) \\ =& s^T(k_p\dot{e} + k_d(\ddot{q} - \ddot{q}_d) + \gamma\mu\dot{e}e^{\mu-1}) \\ =& s^T[k_p\dot{e} + \gamma\mu\dot{e}e^{\mu-1} + k_d(-M\dot{q} - NG(q) \\ & + O(u_{eq}(t) + u_s(t)) + d(t) - \ddot{q}_d)]. \end{aligned} \tag{20}$$

Substitute (16) into (20) produces

$$s^T\dot{s} = s^T[+k_dOu_s(t))] \leq s^T[+k_d|O|u_s(t))]. \tag{21}$$

To ensure (21) is less than zero, $s\dot{s} < 0$, the reaching control law should be chosen as:

$$u_s(t) = K_s sign[s(t)], \tag{22}$$

where $K_s = diag\{K_{s1},\ K_{s2},\ \ldots,\ K_{sm}\}$ represents reaching control gain respect to the upper bound of uncertainties.

Clearly, substituting (22) into (21) we can find that our controller is stable.

5. GREY WOLF OPTIMIZATION

In this paper, the GOW is applied to find the optimal values of the controller parameters. In the GWO, four kinds of wolves are defined:

a) Apha, α, the leaders and are followed by the other wolves.

b) Beta, β, the second level leaders which are the interfaces between the alphas and the other lower-level wolves.

c) Delta, δ, the third level leaders which follow the alphas and betas commands, and submit the commands to the lowes level wolves called omegas.

d) Omega, ω, the lowest level wolves, which are the rest of the wolves population, and all of them are the follower of the commands.

The displacement of alphas, betas, and deltas wolves represent the other wolves movements for hunting the prey, which can be modeled as follows:

$$\begin{aligned} &D = |CX_\rho(t) - X(t)|, \quad C = 2r_r, \\ &X(t+1) = |X_\rho(t) - AD|, \quad A = 2a(t)r_2 - a(t), \end{aligned} \tag{23}$$

where t detects the current iteration, X_ρ and X are the prey, and a grey wolf location respectively, C is a coefficient which is calculated using a random vector, r_1 between 0 and 1, A is a factor located in the interval of $[-2,\ 2]$ appointed by a and r_2, while a is a linear incline vector from

2 to 0 ($a_{max} = 2$, and $a_{min} = 0$), and r_2 is a random vector between 0 and 1. The magnitude of A (which is determined by a) indicates the diversion or attacking toward the prey. If $|A| > 1$ wolves will diverge to search the ambient to detect the prey, while if $|A| < 1$ wolves will converge to attack toward the prey. The term a is initiated to 2, and decreased to 0 during the algorithm.

Therefore, the higher-level wolves (Alpha, Beta, and Delta) positions will guide the positions of other wolves (omegas) to be updated as follows:

$$\begin{aligned} D_\alpha &= |C_1 X_\alpha(t) - X(t)|, \; X_1 = X_\alpha - AD_\alpha, \\ D_\beta &= |C_2 X_\beta(t) - X(t)|, \; X_2 = X_\beta - AD_\beta, \\ D_\delta &= |C_3 X_\delta(t) - X(t)|, \; X_3 = X_\delta - AD_\delta. \end{aligned} \tag{24}$$

Finally, the wolves' positions will be updated as follows:

$$X(t+1) = \frac{X_1 + X_2 + X_3}{3}. \tag{25}$$

As it is defined in the original GWO, the Alpha, Beta, and Delta show the best, the second-best, the third-best solutions respectively. In this paper, to emphasis the Alpha solution more than Beta and Delta, and Beta solution more than the Delta, the emphasis coefficients are added to (25) to weigh X_1 more than X_2, and X_2 more than X_3. Therefore (26) is converted to:

$$X(t+1) = \frac{\alpha_F X_1 + \beta_F X_2 + \delta_F X_3}{3},$$

$$\alpha_F > \beta_F > \delta_F. \tag{26}$$

Considering the emphasis coefficients for GWO, the extended GWO (EGWO) is developed. The pseudo-code for the implemented GWO and EGWO is presented in Fig. 3.

6. EXTENDED GREY WOLF OPTIMIZATION

The parameters for the typical PD controller are chosen as $k_p = diag(200, 200)$ and $k_d = diag(30, 30)$. The sliding surface for the typical SMC is selected as $\lambda = diag(0.1, 0.1)$, $K_s = diag(10, 10)$, $\mu = 5$, and $\gamma = 800$. The GWO and EGWO are used to optimize the NSMC coefficients: $X = [k_{p1}, K_{d1}, k_{p2}, K_{d2}, K_s, \gamma, \mu]^T$.

The number of wolves is selected as 20, and the maximum number of iteration is chosen as 100. The emphasis coefficients in EGWO are selected as $\alpha_F = 1.1$, $\beta_F = 1$, and $\delta_F = 0.9$. The GWO and EGWO are used to find the appropriate values of the HPDSMC controller parameters to minimize the objective functions.

The objective function is defined according to the motion trajectory error of joints as follows:

$$O = \sqrt{\int_0^\infty |e_1(t)|^2 dt} + \sqrt{\int_0^\infty |e_2(t)|^2 dt}, \tag{27}$$

where

$$e_1(t) = q_1(t) - q_{d1}(t),$$

Initialize the grey wolf population X_i ($i = 1, 2, \ldots, n$) randomly in the search space
Initialize a, A, and C
Calculate the fitness of each search agent

X_α = the best search agent (Alpha wolf)
X_β = the 2nd best search agent (Beta wolf)
X_δ = the 3rd best search agent (Gama wolf)
X_ω = the other search agents (Omega wolves)

while(*i <Max number of iterations*)
for *each search agent*
Update the position of the current search agent by (25) *for GWO, and* (26) *for EGWO*
end for
Update a, A, and C
Calculate the fitness of all search agents
Update X_α , X_β and X_δ
$i = i + 1$
end while

Return X_α as the best solution

Fig. 3. The pseudo code for GWO and EGWO.

Table 1. The PDSMC, NSMC, NSMC-GWO, and NSMC-EGWO parameters.

	k_{p1}	k_{d1}	k_{p2}	k_{d2}	k_s	γ	μ
PDSMC	200	30	200	30	10	-	-
NSMC	200	30	200	30	10	800	5
NSMC-GWO	325.4975	11.7131	323.9779	18.4774	5.3635	876.8679	1.0410
NSMC-EGWO	345.1600	10.0639	353.9430	10.7992	5.1602	821.2728	1.0031

$$e_2(t) = q_2(t) - q_{d2}(t). \tag{28}$$

The desired motion trajectory is determined by $q_{d1} = \sin(4.17t)$, and $q_{d2} = 1.2\sin(5.11t)$.

The initial values of the system are selected as:

$$q_1(0) = \pi,\ \ q_2(0) = -\pi,\ \ \dot{q}_1(0) = 0\ \text{ and }\ \dot{q}_2(0) = 0.$$

After optimizing the controller by GWO, and EGWO, the controller parameters are achieved as presented in Table 1. The innovation in EGWO is to set a grading system for a better solution compared with the others. The grading is implemented by setting the coefficients as $\alpha_F > \beta_F > \delta_F$. It seems that EGWO is more powerful than GWO (as it can be seen in the Fig. 7). The EGWO reached to the optimal value in less than 40 iterations, while the GWO could not reach to that point even by 100 iterations. Therefore, Fig. 4 shows the position tracking control of q_1 and q_2 under SMC, PDSMC, NSMC, NSMC- GWO, and NSMC- EGWO. It can be seen from Fig. 4 that using the NSMC-EGWO obtains a faster and more efficient performance to the reference trajectory than the other approaches. The 2-DOF robot manipulator under NSMC-EGWO can reach to the desired trajectory faster than the other controllers, while the NSMC- GWO is also shown an acceptable response having the second grade of performance. Fig. 5 presents the position tracking error of q_1 and q_2 under SMC, PDSMC, NSMC, NSMC- GWO, and

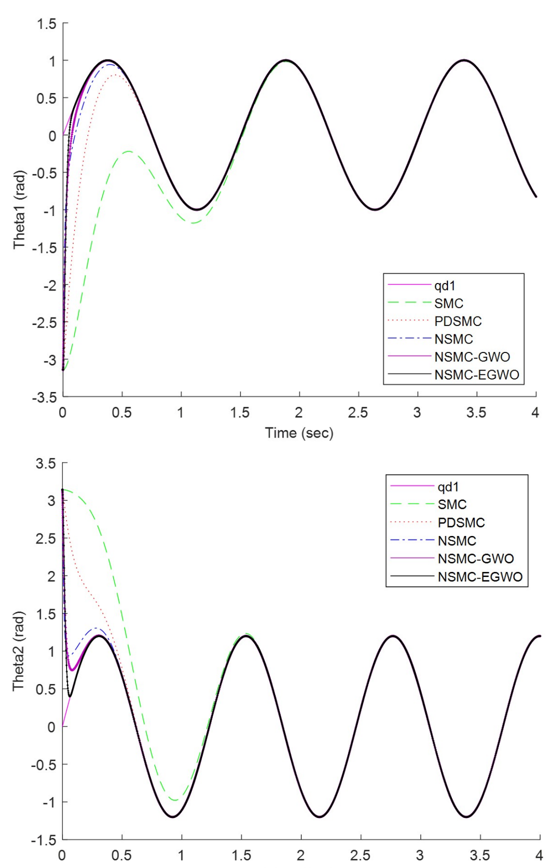

Fig. 4. Position tracking of joints under SMC, PDSMC, NSMC, NSMC-GWO and NSMC-EGWO controllers.

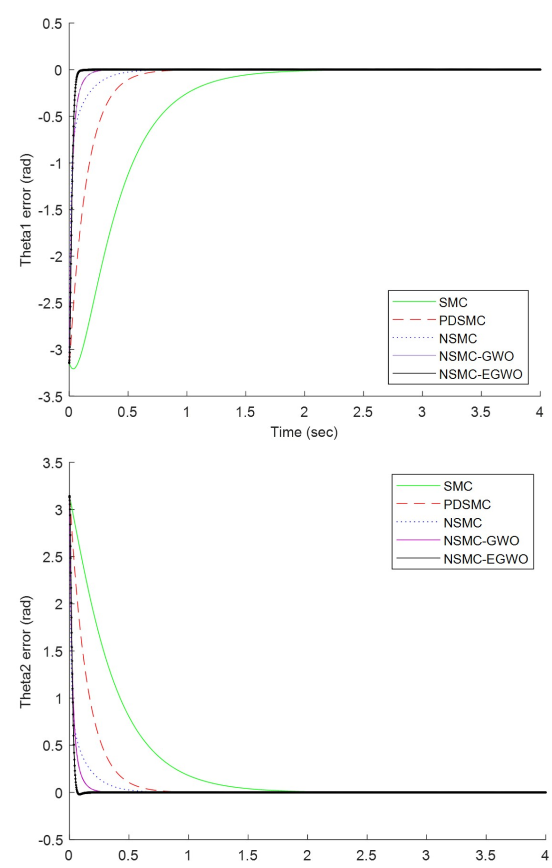

Fig. 5. Position tracking error of joints under SMC, PDSMC, NSMC-GWO and NSMC-EGWO controllers.

NSMC- EGWO. As seen from Fig. 5, NSMC- EGWO has the least error of trajectory tracking followed by NSMC-GWO. According to Figs. 4 and 5, the maximum overshoot is reduced, and settling time is converged to zero in a limited time for q_1 and q_2 under NSMC- EGWO. The velocity of joints 1 and 2 are shown in Fig. 6 under applied controllers. According to Fig. 6, the fastest controller is NSMC- EGWO which makes the 2-DOF robot manipulator settles immediately to the set point in comparison to the other existing approaches. The convergence rate for GWO and EGWO objective functions are shown in Fig. 7. As it can be seen from the Fig. 7, the EGWO not only can reach to the less value for the objective function than the GWO, but also it can find the more optimized solution faster (in less iteration) than the GWO. A random noise is applied to verify the robustness of the proposed control method. Fig. 8 shows that the proposed control method suitably suppressed applied noise.

$$d(t) = 2 * randn(1,1). \tag{29}$$

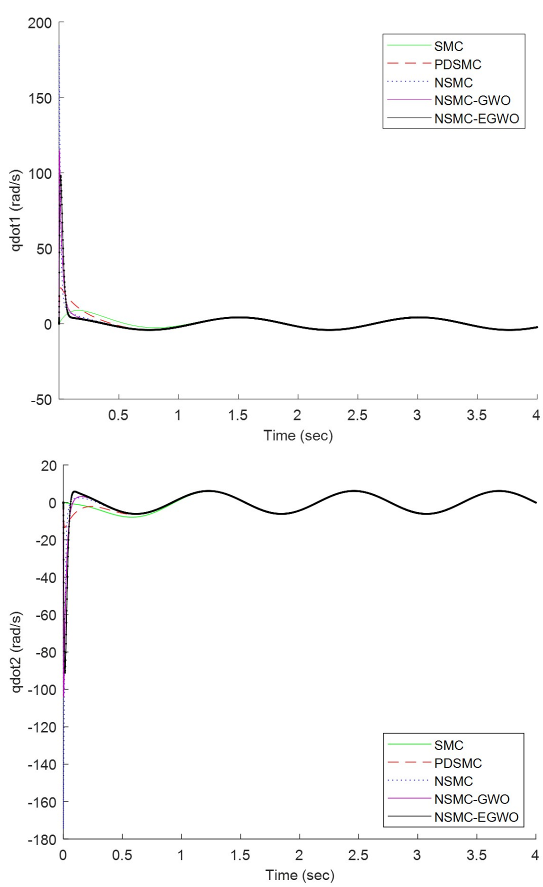

Fig. 6. Velocity of joints under SMC, PDSMC, NSMC-GWO and NSMC-EGWO controllers.

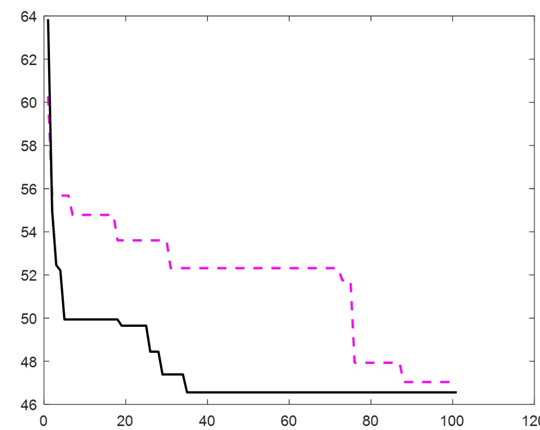

Fig. 7. The convergence rate for NSMC-GWO objective function (——). The convergence rate for NSMC-EGWO objective function (line).

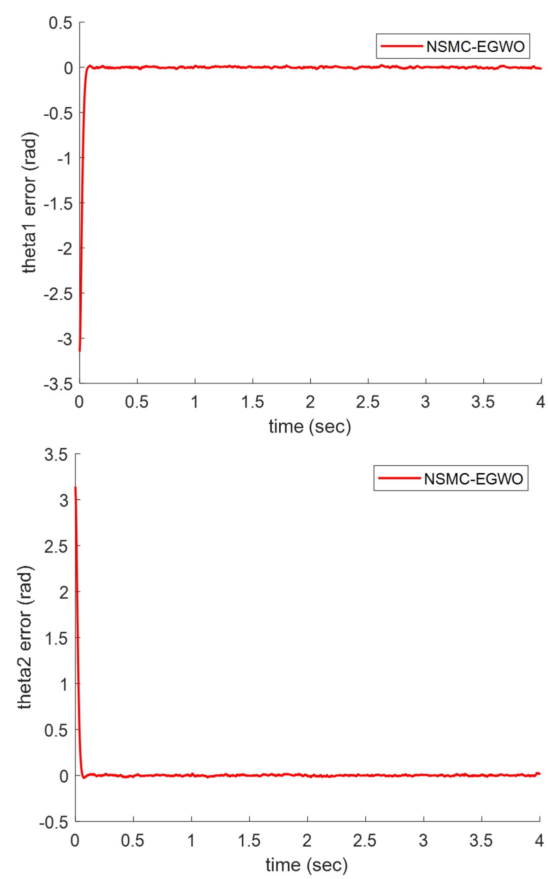

Fig. 8. Position tracking error of joints of the proposed controller under random noise application.

7. CONCLUSION

This paper proposed a new control method to control of a 2-DoF robot manipulator. A new sliding mode surface proposed to improve trajectory tracking. Also, the NSMC method could prove a success in a challenging domain of robot manipulators where the dynamics for each link is expressed by nonlinear, complex, time-varying, and coupled differential equations. But the main issue of the proposed control method was choosing the controller parameters. The GWO, and EGWO then are applied to optimize the proposed control parameters which result in the optimized NSMC-GWO, and NSMC-EGWO, respectively. The numerical simulation results confirmed the effectiveness of the proposed control performance in comparison with four other controllers such as SMC, PDSMC, NSMC, and NSMC-GWO.

APPENDIX A

The parameters of 2-DOF robot manipulator dynamics in (1) can be calculated by

$$q=\begin{bmatrix}\theta_1\\ \theta_2\end{bmatrix},$$

$$B(q)=\begin{bmatrix}(M_1+M_2)L_1^2+M_2L_2^2+2M_2L_1L_2\cos\theta_2 & M_2L_2^2+M_2L_1L_2\cos\theta_2\\ M_2L_2^2+M_2L_1L_2\cos\theta_2 & M_2L_2^2\end{bmatrix},$$

$$C(q,\dot{q})=\begin{bmatrix}-M_2L_1L_2\sin\theta_2(2\dot{\theta}_1\dot{\theta}_2+\dot{\theta}_2^2)\\ -M_2L_1L_2\sin\theta_2\dot{\theta}_1\dot{\theta}_2\end{bmatrix},$$

$$G(q)=\begin{bmatrix}-(M_1+M_2)gL_1\sin\theta_1-M_2gL_2\sin(\theta_1+\theta_2)\\ -M_2gL_2\sin(\theta_1+\theta_2)\end{bmatrix},$$

$$\tau=\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix}.$$

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