Dynamic Dandelion Optimization-Based Model Predictive Control for Accurate Tracking of a 6-DOF Robot Manipulator

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This paper proposes an optimized control strategies for a dynamics 6-link robot manipulator using Model Predictive Control (MPC) and traditional Computed Torque Control (CTC). Two optimization methods are used for tuning of MPC controller, namely MPC- based Dandelion Optimization (DO) and MPC- based Genetic Algorithm (GA). The strategies are assessed in terms of performance indices based time- domain, settling time, rise time, overshoot percentage, and steady-state error (SSE). Simulation results depicted that traditional CTC suffers from higher control effort and slower transient response, mainly for links with high order. In contrast, MPC-based control strategy significantly improve dynamic performance and tracking accuracy. Among the tested approaches, MPC- based DO achieves minimal overshoot, smoother torque profiles, fastest convergence, and the lowest SSE across all six robotics links. The attained MATLAB/SIMULINK results confirm and prove that optimized MPC controller, especially MPC- based DO, offers an efficient and robust control solution for high DOF robotic manipulators.

Keywords: *Compute torque control; Dandelion Optimizer; Genetic algorithm; Model predictive control; Nonlinear control; Six link robotic manipulator.*

1. INTRODUCTION

The control of robotic manipulators has evolved into a significant research area in industrial robotics, driven by growing demands for intelligent automation capabilities to enhance precision, adaptability, and operational efficiency. The researchers' interest in developing new methods for robots has increased. Lately, robot manipulators have been used in various applications, such as surgery [1,2], society [3], school [4], industry [5-8], etc. The control system plays a critical role in manipulator robustness. Many approaches are listed in the literature for robot manipulators.

Despite progress in control system design, PID control technology remains the most widely used strategy in the industry because it's easy to design and implement [9]. In [10], a trajectory tracking control of a two-link robotic arm is investigated by using a PID controller. Additionally, this technique has been tested in a simulation.

Furthermore, a combination of proportional-integral-derivative (PID) controllers and linear quadratic regulator (LQR) is described in [11] and [12] to control a parallel manipulator. Additionally, nonlinear Self-tuning controllers are a used techniques that control robotic systems [13]. However, one of the main limitations of this type PID is the nonlinearity of the system to be controlled, which affects robustness and precision, making it difficult to use for many advanced robotic applications. Hybrid approaches such as PID plus feed–forward or PID plus adaptive control are often used to improve performance.

Several research studies have been conducted on utilizing sliding mode control (SMC) for robotic manipulators [14]. A SMC was introduced in [15] for a 2-DoF manipulator. A nonlinear disturbance observer is employed to enhance robustness in the face of uncertainties of the robot manipulator. In [16], a Sliding Mode Control (SMC) is compared with a PID controller on a 2-link robotic manipulator in terms of trajectory tracking performance, considering the nonlinear dynamics and uncertainties of the robot manipulator. Additionally, in [17], a nonlinear integral sliding mode control approach was developed for a 2-link robotic arm. Also, the simulation of the used manipulator is compared with a conventional PID controller.

Article [18] proposed a visual servo controller for an apple-harvesting manipulator using Sliding Mode Control (SMC) combined with a fuzzy neural network. This combination reduces the chattering commonly associated with the variable structure of the sliding mode and improves the control of the dynamic system. A comparison is made between the proposed controller and a conventional PID controller, as well as a standard SMC. The proposed fuzzy neural network SMC algorithm exceeds the PID controller and the SMC. The work presented in [19] concerns a SMC-PID control system applied to a tender tea bud-picking manipulator. The proposed controller was compared with a stand-alone SMC and a conventional PID, and it surpass both in terms of jitter and response time. While SMC is powerful for robust control in uncertain environments,

Received: March 2026, Accepted: May 2026
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doi: 10.5937/fme2603438A

its flaws, especially chattering and high control effort, make it less suitable for precision robotics.

Recently, many control methods have been com–bined with fuzzy logic. For instance, an adaptive fuzzy terminal Sliding Mode Control (SMC) technique has been introduced [20] , [21] for controlling uncertain systems under disturbances. Also, in [22], the recursive back-stepping method for non-affine stochastic nonlinear switched systems is used to propose a robust adaptive fuzzy tracking controller. In [23], the Fuzzy logic controller is used as the central controller, and in [24], it is used as a part of the control system estimator. Fuzzy controller is used in controlling many other sys–tems like [25] Permanent Magnet Synchronous Motor (PMSM) speed control, [26] Autonomous underwater robots, [27] Internet of Things (IoT) and Fuzzy Logic for water and energy saving, [28] Synchronization for two Chua systems, [29] Designed for non-minimum phase DC-DC converters, and [30] Impedance control for robot manipulators. Although a fuzzy controller helps handle uncertainty, it takes more time to make decisions, which can be a problem for robots needing fast, real-time responses. Additionally, tuning the sys–tem properly isn't easy; it often requires expert know–ledge to work optimally.

There are also other control techniques used in the control of robot manipulators, such as the computed torque controller (CTC). Authors in [31] introduce a PID computed torque control (PID-CTC) method for the robot manipulator to track a specific position. Compared with the traditional position control method, the results show that the PID-CTC control shows low error and high accuracy. Article [32] introduced a design of Com–puted Torque Control (CTC) for ED 7220C, a vertical articulated serial arm 6 DOF. The algorithm is imple–mented in MATLAB/Simulink. Simulation results show the efficacy of the presented approach in terms of trajectory tracking. Also, in [33], to improve tracking performance on high-precision motion control of heavy-duty parallel manipulators, conventional independent joint control and computed torque control schemes are modified by introducing nonlinear loop gains. Compa–risons between the proposed controllers and conven–tional controllers reveal that the tracking precision of the platform is enhanced, and CTC demonstrates the best tracking precision.

The research in [34] proposes a CTC method com–bined with an online least squares support vector reg–ression algorithm for a two-link robotic arm under disturbance and model uncertainty. It uses a machine learning technique to obtain the model. This work aims to enhance the performance of the control and establish an adaptive construction where the model of the system does not require to have prior information. It is compared with the computed torque control approach and demonstrates the superiority of the proposed approach. Furthermore, a CTC for a 5-DOF robot mani–pulator is presented in [35] in terms of the end-effector position's task space. Manipulator modeling in SolidWorks helped in obtaining the robot dynamics. Moreover, MATLAB/SimMechanics environment was utilized to generate the block diagram of the multi-body system. The system motion Equation is formed consi–dering friction. The CTC is used in conjunction with linear PD and PID controllers that incorporate feedback. The simulation results prove that PD-CTC is effective and significantly superior to PID-CTC. In [36], an advanced GA-based optimal control scheme is proposed for a tracker robot with machine vision capability. GA is used to obtain the optimum values of control constants based on a suitable cost function. A simulation study shows the superiority of the GA-based controller. Addi–tionally, the proposed visual tracker robot has been developed, and its performance in tracking a moving object on both circular and butterfly-shaped trajectories in the camera coordinates is investigated. The CTC technique, combined with a classical PD/PID controller (PD-CTC, PID-CTC), is employed to eliminate nonli–near dynamics, allowing the system to operate with higher tracking accuracy, lower feedback gain, increa–sed suitability for conformal control, and reduced ene–rgy consumption. One of the simple design methods for controlling a robot manipulator is the model-based PD/PID controller, which is an effective control method.

Recent research has highlighted MPC as a powerful controller for robotic systems, especially in industrial control applications [37]. Unlike traditional methods, MPC is ideal for complex tasks, such as high-speed assembly, due to its ability to predict and optimize future behavior in real time. Now, it is widely used in many research studies. A nonlinear MPC method was developed for cable-controlled parallel robots to address their dynamic challenges and improve control accuracy [38]. A fast nonlinear MPC approach was proposed for parallel manipulators to handle their nonlinear dynamics and improve control performance [39]. In [40], a model-free adaptive predictive tracking controller for robotic arms has been developed. Their innovative approach uses only the robot's input/output data to predict and improve movement accuracy. When compared with conventional PID control in simulations, the new method reduced position errors by 90%, achieving just a 1 mm error compared to PID's 10 mm error.

In [41], a high-frequency nonlinear model predictive control (MPC) controller for a 7-DOF KUKA LWR iiwa R820 14 [42] robot arm is introduced using dif–ferential dynamic programming (DDP). It computes torque with two methods: open-loop and closed-loop. The closed loop worked better than the open loop. In [43], An MPC algorithm is proposed for rigid mani–pulators. A combination of MPC with a generalized proportional-integral observer (GPIO) is examined on a simulated 2-link rigid arm. They consisted of the following: MPC (feedback controller) for trajectory tracking and GPIO (disturbance estimation) for genera–ting feedforward compensation. It exhibited faster settling time and less overshoot compared to integral MPC and a baseline MPC. Article [44] introduced a MPC approach in order to controlling the path of a 2-DOF sweet potato transplanting robot. An MPC handles the system delay problem and improves the system's performance. MPC is a suitable choice for robotics, as it optimizes future movements for precision while res–pecting physical limits. This advantage makes it ideal for dynamic, safety-critical tasks, such as those invol–ving industrial robot manipulators.

Recent studies on robotic control have made valu–able contributions while leaving certain gaps. Slavković et al. (2022) developed an offline programming system for a 4-axis hybrid robot, but it does not use advanced control strategies beyond kinematics and assumes idea–lized conditions without friction or disturbances [45]. Zhou et al. (2025) proposed a two-level variable-impe–dance control for dual-arm manipulators, advancing force control through experimental validation. However, their work used custom-built rather than commercial manipulators; their stability proof relies on the Routh criterion (while a Lyapunov approach could offer stron–ger guarantees for nonlinear dynamics); and their com–parison excludes modern control techniques and rein–forcement learning [46]. To build on these contributions, our paper proposes a novel multi-controller framework integrating CTC and MPC under system uncertainties.

Robotic control systems have evolved significantly to meet the demands of various practical applications, including intelligent manufacturing, logistics, precision surgery, and healthcare. Fundamental applications of robots rely on control strategies, such as MPC and CTC, because these methods enable real-time motion planning while respecting safety constraints, which is essential for human-robot collaborative environments [47]. The scientific merit of MPC and CTC lies in their ability to overcome theoretical challenges, such as system non–linearities, model uncertainties, and external distur–bances, while ensuring stability and good performance. From an engineering perspective, these approaches allow us to create reliable, adaptive, and safe robotic systems that consequently enhance productivity, reduce human error, and operate effectively in complex, uns–tructured environments.

The distinct contribution of this paper is threefold. First, a unified comparative structure is established to evaluate CTC, MPC- based GA, and MPC- based DO for a 6-link robotic system manipulator under the same control and dynamic constraints. Second, the impact of optimization techniques on performance of MPC is examined using different comprehensive metrics of performance, including rise time, settling time, torque smoothness, steady-state error, and accuracy of tracking. Third, the obtained simulation results prove that dynamic optimization based MPC strategy considerably outper–forms both traditional CTC and GA- tuned MPC, mainly for distal links, thus highlighting the challenges related to nonlinear coupling in high-DOF robotic systems.

This paper is structured as follows: Section 2 provides a description of a robot manipulator with six links and its dynamical model. In Section 3, the control techniques used for controlling the robot using the MPC and CTC approaches are explained. The optimization techniques such as DO and GA that are used to obtain the optimal values of the control parameters are described in Section 4. A comparative study and simulation results are presented in Section 5. Finally, a conclusion is addressed in section 6.

2. DYNAMIC MODEL

The proposed six robotic system is modelled mathe–matically to evaluate the designed controllers in this paper. Besides, the selected system to be proposed for the study is PUMA 560 as the robotic system for the study. Figure 1 shows an industrial robot called PUMA 560 with 6 degrees of freedom. All links have revolute angles; each has one, and the last three are in the wrist. The calculations of the kinematic model are listed in detail in [48].

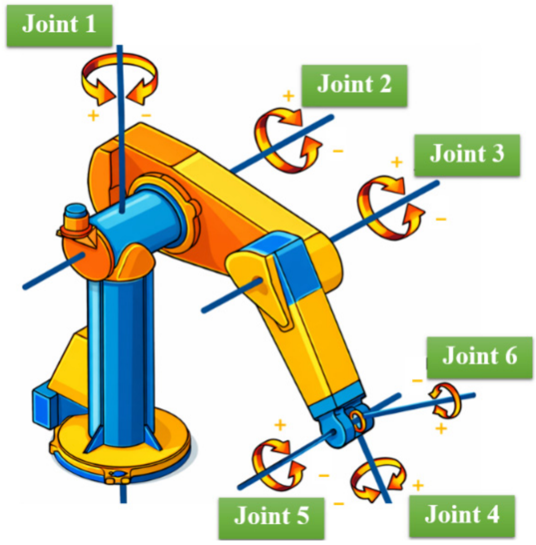

Figure 1. PUMA560 Six Link Robot Arm Manipulator

The robot's dynamic model investigates the relati–onship between the joint actuator torques and the mo–tion resulting from this torque. The accurate dynamic model of the robot manipulator is useful in mechanical design analysis, manipulator movement simulation and design of motion control systems such as predictive control [49], sliding mode control [50] and computed torque control [51]. Lagrange-Euler approach is a simple well-known energy-based approach that can be used to deduce the dynamic Equations of robot mani–pulator [52]. For the same manipulator, Lagrange-Euler approach gives the same Equations of motion as the Newton-Euler approach. The following subsection des–cribes how the dynamic Equations are derived.

2.1 Lagrange-Euler (L-E) Equation

This subsection briefly describes the derivation of L-E Equation. More details are found in [53]. The first step to determine the L-E equations is to calculate system's Lagrange as in Eq. 1.

$$L = K - P \tag{1}$$

where L is Lagrangian, K is Kinetic energy and P is Potential energy. According to [54-56]. the previous Equation can be used to derive the Lagrange equations of motion of the robotic system as given in Eq. 2.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \theta_i}\right) - \frac{\partial L}{\partial \theta_i} = \tau_i \qquad i = 1,2,\ldots n \tag{2}$$

where θ_i is the joint-variable vector and $\theta \in R^n$, τ_i is the general nonpotential force which drives θ_i. Using Equations 1 and 2, Equations 3, 4 and 5 can be deduced for the 6-link robot manipulator [48].

$$M(\theta)\ddot{\theta}+N(\theta,\dot{\theta})=\tau \tag{3}$$

$$N(\theta,\dot{\theta})=C(\theta,\dot{\theta})\dot{\theta}+G(\theta) \tag{4}$$

$$Y=\ddot{\theta} \tag{5}$$

where, $\theta, \dot{\theta}$ and $\ddot{\theta}$ are respectively 6×1 vectors of generalized joint coordinates (Position, velocities and accelerations).

The calculation of dynamic behavior for the positions, velocities and accelerations of the robot manipulator joints in case of a certain input torque vector are depicted in Eq.3. Its LHS contains a linear part and a nonlinear part. Both parts are indirect functions of time because they are functions of the position vector θ and the velocity vector $\dot{\theta}$ which are functions of time. This means that M and N should be calculated online during any simulation. Beside that the nonlinear term N is function of time, it depends on the friction forces and the gravity loading. Further information about the constructions and expressions of M and N can be found in [48].

3. CONTROLLERS DESIGN

This section proposes two types of controllers: MPC and CTC. First, MPC is divided into two steps: feedback linearization to make the model linear, and then an MPC will be designed. Second, CTC is based on the feedback linearization technique. It makes the model linear by canceling the manipulator's nonlinearities and applying precisely the torque needed to overcome the inertia of the actuators.

3.1 Feedback Linearization

This technique aims to turn the nonlinear dynamic system into a linear dynamic system in order to linear control techniques can stabilize it [57][58]. This paper provides the feedback linearization controlling method for a six-degree of freedom robot manipulator given by Eq. 6. To do that, the output (Y) given by Eq. 7 must be differentiated until the control output (τ) appears. Here, t appeared after two derivatives. It means that system's relative degree was two. The second derivative of Y is given by

$$\ddot{Y}=\ddot{\theta}=M(\theta)^{-1}\left(-C(\theta,\dot{\theta})-G(\theta)+\tau\right)=v \tag{6}$$

$$v=\left[v_1 v_2 v_3 v_4 v_5 v_6\right]^T \tag{7}$$

where v is synthetic control vector.

From Eq. 6, the relationship between a synthetic control and the actual control is found, and it represents the feedback linearization control law.

$$\tau=M(\theta)v+N(\dot{\theta},\theta) \tag{8}$$

Substitute Eq. 8 by 3; It was found that the nonlinear model of the 6 DOF robot manipulator becomes a linear double integrator system. By the way, the relative degree was 2, which means that the linearization of the system happened, and each joint became a linear system. The six linear system's transfer functions are given by:

$$\begin{aligned}&\frac{\theta_1(s)}{v_1(s)}=\frac{1}{s^2} \quad \frac{\theta_2(s)}{v_2(s)}=\frac{1}{s^2}\\&\frac{\theta_3(s)}{v_3(s)}=\frac{1}{s^2} \quad \frac{\theta_4(s)}{v_4(s)}=\frac{1}{s^2}\\&\frac{\theta_5(s)}{v_5(s)}=\frac{1}{s^2} \quad \frac{\theta_6(s)}{v_6(s)}=\frac{1}{s^2}\end{aligned} \tag{9}$$

where s, the Laplace transform variable.After achieving linearization of the nonlinear system, the next step is applying the model predictive control for a linear model of the six-DOF robot.

3.2 Model Predictive Control Design

Previously, the feedback linearization was done, and by solving Eqs. 8 and 3, the following six equations of a linear system are obtained.

$$\begin{aligned}&\ddot{\theta}_1=v_1, \quad \ddot{\theta}_2=v_2,\\&\ddot{\theta}_3=v_3, \quad \ddot{\theta}_4=v_4,\\&\ddot{\theta}_5=v_5, \quad \ddot{\theta}_6=v_6\end{aligned} \tag{10}$$

The system represented by Eq. 10 can be stabilized easily by using the PD controller given by:

$$\begin{aligned}v_1&=k_1(\theta_{1d}-\theta_1)+k_2(\dot{\theta}_{1d}-\dot{\theta}_1)\\v_2&=k_1(\theta_{2d}-\theta_1)+k_2(\dot{\theta}_{2d}-\dot{\theta}_1)\\v_3&=k_1(\theta_{3d}-\theta_1)+k_2(\dot{\theta}_{3d}-\dot{\theta}_1)\\v_4&=k_1(\theta_{4d}-\theta_1)+k_2(\dot{\theta}_{4d}-\dot{\theta}_1)\\v_5&=k_1(\theta_{5d}-\theta_1)+k_2(\dot{\theta}_{5d}-\dot{\theta}_1)\\v_6&=k_1(\theta_{6d}-\theta_1)+k_2(\dot{\theta}_{6d}-\dot{\theta}_1)\end{aligned} \tag{11}$$

where $[\theta_{1d}\theta_{2d}\theta_{3d}\theta_{4d}\theta_{5d}\theta_{6d}]^T$ is a desired joint vector. It should be noted that the PD controller is not physically realizable because the gain becomes infinite at high frequencies [59]. To solve this problem, a PD controller is used as a phase lead compensator, or applying another filtering method.The closed-loop system shows a second-order system's behavior and k1 and k2 may be selected as:

$$k_1=\omega_0^2 \text{ and } k_2=2\zeta\omega_0 \tag{12}$$

where, ω_0 is natural frequency, ζ is damping ratio.A large number of poles were found when applying the gains that were chosen in the previous step. The function of MPC here is to limit this domain to optimize the cost function. This function will be detailed in the following parts.Initially, the MPC controller will be applied to the first link of the robot [60–62]. Then, similarly to the other links. Assuming $v_1(t)=v_1$ is constant in the time interval [t,$t+h$] where h is the prediction horizon time. Using Eq. 11, the prediction model is given as follows [63]:

$$\dot{\theta}_1(t+h) = v_1 h + \dot{\theta}(t)$$
$$\theta_1(t+h) = \frac{1}{2}v_1 h^2 + \dot{\theta}_{1(t)}h + \theta_1(t) \quad (13)$$

After that, since the reference angle of the first link θ_{1d} is constant, the suggested one-horizon time quadratic cost function that stabilizes the system is defined by:

$$J = e_1^2(t+h) + \rho \dot{e}_1^2(t+h) \quad (14)$$

where $e_1(t+h) = \theta_{1d} - \theta_1(t+h)$ is predicted angle error, $\dot{e}_1(t+h) = \theta_{1d} - \dot{\theta}_1(t+h)$ is predicted velocity error, h is horizon time, ρ is weight. h and ρ are control parameters (positive real constant). Now, substitute Eq. 13 in 14 to complete the criterion (J). The main purpose of the introduced control law is to get the suitable value of the constant v that makes $\frac{\partial J}{\partial v_1}$ equal to 0, therefore minimizing J. The obtained MPC controller is given by

$$v_1 = k_1(\theta_{1d} - \theta_1(t)) - k_2\dot{\theta}_1(t) \quad (15)$$

The control gains is given by

$$k_1 = \frac{2}{h^2 + 4\rho} \text{ and } k_2 = \frac{2h^2 + 4\rho}{h^3 + 4\rho h} \quad (16)$$

The block diagram of the closed-loop system is shown in Figure 2.

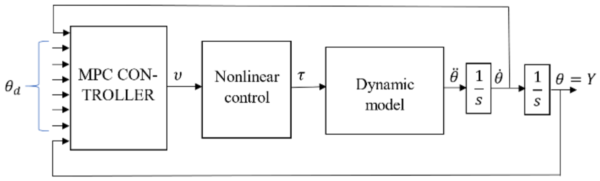

Figure 2. Closed-loop system

Using the same controller for the second link and its equation will be as follow

$$v_2 = k_1(\theta_{2d} - \theta_2(t)) - k_2\dot{\theta}_2(t) \quad (17)$$

Regarding the performance of the system, the goal was the system to follow the second order system in behavior as follow:

$$\frac{\theta_1(s)}{\theta_{1d}(s)} = \frac{\omega_0^2}{s^2 + 2\zeta\omega_0 + \omega_0^2}$$
$$\frac{\theta_1(s)}{\theta_{1d}(s)} = \frac{k_1}{s^2 + k_2 s + k_1} \quad (18)$$

Considering Eqs. 18 and 15 gets the following:

$$2\zeta\omega_0 = \frac{2h^2 + 4\rho}{h^3 + 4\rho h} \quad (19)$$

$$\omega_0^2 = \frac{2}{h^2 + 4\rho} \quad (20)$$

The weight factor obtained from Eq. 20 is

$$\rho = \frac{2 - (\omega_0 h)^2}{4\omega_0^2} \quad (21)$$

Substituting Eqs. 21 in 19, the following equation of the second-order system is given by

$$\omega_0^2 h^2 - 4\zeta\omega_0 h + 2 = 0 \quad (22)$$

where h is the variable I want to get. Using the following equation,

$$\lambda = \omega_0 h \quad (23)$$

The Eq. 22 becomes

$$\lambda^2 - 4\zeta\lambda + 2 = 0 \quad (24)$$

By solving the previous second-order equation,

$$\lambda_{1,2} = 2\zeta \pm \sqrt{4\zeta^2 - 2} \quad (25)$$

This mean $\lambda_{1,2}$ real if and only if

$$4\zeta^2 - 2 \geq 0,\ \zeta \geq \sqrt{2}/2 \quad (26)$$

The second condition to get positive weight factor (ρ) is $\lambda_1^2 < 2$. Because the larger solutions never achieve this inequality. Therefore, the smaller solution was kept. The equation will be as follow:

$$\lambda_{1,2} = 2\zeta - \sqrt{4\zeta^2 - 2} \quad (27)$$

After choosing the parameters carefully, it is pos–sible now to determine the parameters h and p from Eqs. 21, 23 and 27. To guarantee the best values of w and h are chosen, two optimization techniques have been used. This techniques are called dandelion optimizer and genetic algorithm. All this work has been done using MATLAB/Simulink.

3.3 Computed Torque Control

CTC approach is a robust nonlinear controller that is used widely in robot manipulator control. CTC is based on feedback linearization that cancels all the nonli–nearities of the manipulator and applies exactly the tor–que needed to overcome the inertia of the actuators [52,64]. As a result, this controller work very well when both physical and dynamic parameters are well known. However, when there are uncertainties in dynamic parameters in the robot manipulator, the controller has no suitable performances [65]. The main idea of CTC will be illustrated in the following lines. Since the dynamic equation of the manipulator is given as in Eqs. 3 and 6. It is assume that τ as given in Eq. 28.

$$\tau = M(\theta)[\ddot{\theta} - v] + N(\theta, \ddot{\theta}) \quad (28)$$

Where v is a variable to be determined. This assumption has two reasons. The first is to cancel the nonlinear term and the second is to introduce the second derivative of the tracking error which is defined as:

$$e(t) = \theta_d(t) - \theta_a(t) \quad (29)$$

Substituting τ from Eq. 34 into Eq. 3 one get

$$M(q)(\ddot{e} - U) = 0 \quad (30)$$

Eq. 30 means that the term between the brackets should equal to zero since $M(\theta)$ is a non-singular matrix. Now, assuming that

$$U = -k_v \dot{e} + k_p e \quad (31)$$

where k_v and k_p are diagonal matrices. Their elements are constants. From Eqs. 30 and 31, one gets

$$\ddot{e} + k_v \dot{e} + k_p e = 0 \quad (32)$$

Eq. 32 means that the tracking error vector is ensured to be zero and its dynamic behavior depends on the gain matrices k_v and k_p. Choosing the values of k_v and k_p is very simple because Eq. 32 represent a group of linear second order differential equation which are well known in the linear control theory. Returning to the required joint torques we will find it as given in Eq. 33.

$$\tau = M(q)\left(\ddot{q}_d + K_v \dot{e} + K_p e\right) + N(q, \dot{q}) \quad (33)$$

Since the required torque vector that ensures zero tracking error depends on the tracking error vector and its derivative, the controller is referred to as PD-Computed torque controller[66]. The CTC is implemented using MATLAB/SIMULINK as depicted in Eqs. (34 and 35). Eq. 34 demonstrates the tracking error vector (e) and the desired trajectory to produce the term E.

$$E = \ddot{q}_d + k_v \dot{e} + k_p e \quad (34)$$

The derivative of the actual trajectory vector is easily derived using a derivative block in Matlab package. Eq. 35 is used to produce the required torque vector.

$$\tau = M(q)E + N(q, \dot{q}) \quad (35)$$

The complete CTC model is presented in Fig. 3. Based on the construction of the suggested controller which has θ_d as input vector, θ as a feedback vector and output τ, the output will be connected to the robot to get the full feedback configuration (see Fig. 3).

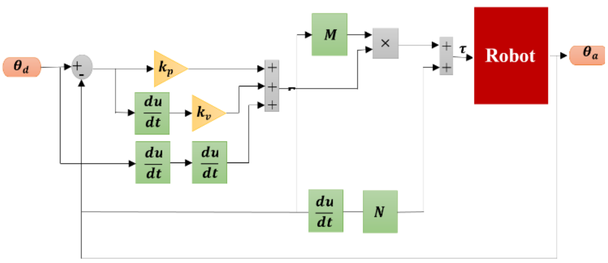

Figure 3. Overall system blocks

3.4 Novelty of the Proposed Strategy

The proposed control methodology demonstrates a comparative framework- based hybrid intelligent control by integrating MPC with two optimization approaches namely, DO and GA techniques to enhance the performance of tracking trajectory for the 6-DOF robotic manipulator. Besides, the suggested optimized strategies are compared with the traditional CTC- based GA to assess the efficiency of the proposed methodologies.

The novelty of this study lies in the using and comparative evaluation of MPC- based DO and MPC- based GA strategies to optimally tune the parameters of MPC controller, which improves the response, minimizes tracking error, and enhances the stability of the system. In addition, these combinations decreased overshoot, allows faster convergence, and enhanced robustness of the system. Moreover, the proposed approach improves the overall efficiency of control by attaining precise tracking of the trajectory with smoother action of control and lower error of steady-state. Unlike traditional control approaches that depend on trial and error methods for selection of the controller's parameter, the obtained results prove that the MPC- based DO attains superior and distinct performance compared with the MPC- based GA and the traditional CTC- based GA in terms of performance criteria for 6-DOF robotic systems.

4. RESULTS AND DISSCUSSIONS

The optimization techniques used for finding the optimal parameters for the controllers are discussed in the following. The optimization techniques used in optimizing MPC parameters are DO and GA. They have operated under the same conditions, such as parameter ranges, population size, number of iterations, and objective functions. The purpose was to see which would give the best choice and, subsequently, the best performance. Optimization conditions will be stated as follows. For the DO algorithm, the setting for the algorithm such as number of search agents (N) = 50, maximum number of iterations =100, lower bound (LB) = [0.1 0.71], upper bound (UB) = [1 3]. The objective function is defined as in the following Equation in terms of error (e) and overshoot (OS).

$$\text{Objective Function} = 0.5*\text{mean}(\text{norm}(e)) + 0.5*\min(\text{norm}(OS)) \quad (36)$$

Moreover, the GA algorithm is tuned via trial and error method as population size = 50, Generations = 100, LB, and UB are the same as in DO algorithm to achieve the equilibrium comparison between the proposed algorithms. Besides, the objective function also is the same as in Eq. 36. The optimization technique used in optimizing CTC parameters are GA. It is used to get the best values of kp and kd. The optimization conditions will be stated as follows; such as LB = [0 1] and UB =[1 25]. The simulation results for the two suggested strategies, MPC and CTC, which are implemented in MATLAB/Simulink. The controller's parameters were optimized using DO and GA. The performances were evaluated based on rise time, overshoot, and steady-state error under identical conditions. Figs. 4 and 5 demonstrate the comparison metrics based on chart aids for performance indices and SSE respectively.

The desired orientations used for the six links robot in both controllers were θ_{1d} = 1.0472 rad, θ_{2d} = 1.571 rad, θ_{3d} = 0.0940 rad, θ_{4d} = 2.5326 rad, θ_{5d} = 0.9743 rad and θ_{6d} = 0.3734 rad, respectively. Table 1 gives the values of the gains optimized by each optimization technique for the two controllers.

The simulation results for the 6-link robotic system prove that all investigated control strategies are proficient of tracking the command joint trajectories;

however, visible differences appear in steady-state accuracy, transient response, and effort of control (see Fig. 4 to Fig. 23). The traditional CTC shows larger deviations in transient response and slower conver–gence, mainly in higher order links where effects of nonlinear coupling are more vital and significant. These restrictions highlight the CTC sensitivity to model dynamic interactions and uncertainties among the links.

The proposed MPC considerably enhances the overall performance of the system. The MPC- based GA method decreases settling time and rise time compared to approach of CTC and achieves a significant decre–asing in steady-state error through all system links. Fur–thermore, MPC- based GA offers smoother responses of joint and improved robustness, indicating the effecti–veness of GA- based coefficients optimization in imp–roving performance of predictive control.

Analyzing Table 1, it is observed that the DO and the GA have approximate results. Also, between the MPC and the CTC, the rising time and the settling time of the MPC are smaller than that of the CTC (see Figs 4 and 5). Moreover, the steady-state error of the MPC is much smaller than CTC. In order to show these differences in results, the following simulation results are given in Figs 4 and 5. The following figures rep–resent the responses of actual angels, torques, and errors for each link.

Fig. 6 to Fig. 11 gives a comparison between the convergence of joint angles corresponding to the desired angles in the case of CTC and MPC by DO and GA. It is observed that MPC gives faster and more accurate than CTC at all links. Fig. 12 to Fig. 17 shows a comparison between the torques of the robot that exits from CTC and MPC (DO and GA). Fig. 18 to Fig. 23 displays a compa–rison between the convergence of the robot angles tow–ards zero using CTC and MPC (DO and GA) approaches.

Table 1 Gains and step information for all links

	CTC (GA)						MPC (GA)								MPC (DO)							
	Gains		Performance Criteria				Gains				Performance Criteria				Gains				Performance Criteria			
	kp	kd	Ts	Tr	OS	SSE	zeta	Wo	k1	k2	Ts	Tr	OS	SSE	zeta	Wo	k1	k2	Ts	Tr	OS	SSE
Link 1	5.2441	4.58	2.569	1.473	0	7.481×10^{-9}	0.983	2.981	8.886	5.861	1.667	1.033	0.210	4.783×10^{-11}	0.983	3	7.474	5.339	1.656	1.026	0.210	4.441×10^{-11}
Link 2			2.569	1.473	0	1.122×10^{-8}					1.906	1.087	0	1.546×10^{-12}					1.893	1.080	0	8.671×10^{-13}
Link 3			2.569	1.473	0	6.715×10^{-10}					1.768	1.048	0	1.213×10^{-12}					1.757	1.042	0	1.113×10^{-12}
Link 4			2.569	1.473	0	1.809×10^{-8}					1.890	1.084	0	9.400×10^{-12}					1.878	1.077	0	7.863×10^{-12}
Link 5			2.569	1.473	0	6.960×10^{-9}					1.890	1.084	0	3.617×10^{-12}					1.878	1.077	0	3.025×10^{-12}
Link 6			2.569	1.473	0	2.667×10^{-9}					1.890	1.084	0	1.386×10^{-12}					1.878	1.077	0	1.159×10^{-12}

where, T_s is a settling time in second, T_r is a rising time in second, OS is an overshoot in % and SSE is a steady state error in rad.

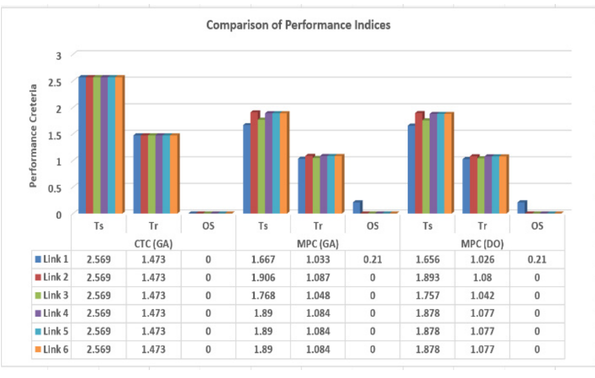

Figure 4. Comparison of Performances Indices

Among the evaluated control strategies, MPC- based DO methodology consistently provides the best simula–tion results for robotic system control (see Table 1). It attains the fastest convergence to the reference trajecto–ries, negligible the effect of overshoot, and the lowest error for steady-state situation for all six robot links. The enhan–cement is mainly evident in distal robot links, where MPC-based DO efficiently compensates for high and strong nonlinearities and coupling of inter-link. Additi–onally, the torque control produced by MPC- based DO demonstrates smoother profiles and decreased peak values, which is valuable for energy efficiency and actuator longevity.

Overall, the obtained results approve that optimized MPC control strategies outperform traditional CTC in terms of dynamic response, accuracy, and control smo–othness. The MPC- based DO strategy, in particular, exhibits superior ability in dealing the complexity of high DoF robotic manipulators, creation it an efficient and robust solution for applications of precise motion control.

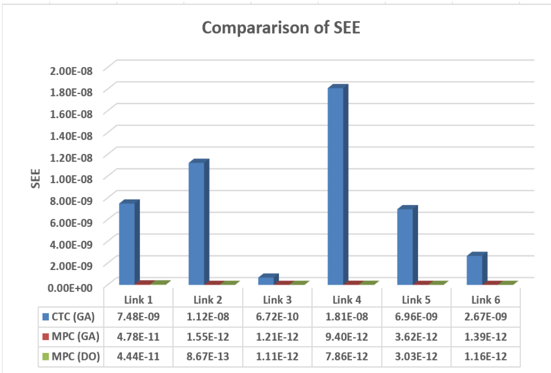

Figure 5. Comparison of SSE for All Links

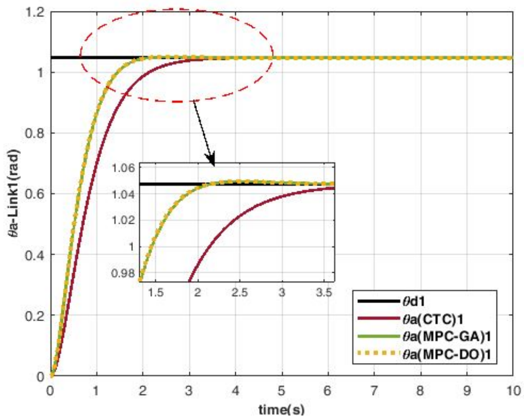

Figure 6. Performances of controllers for link 1

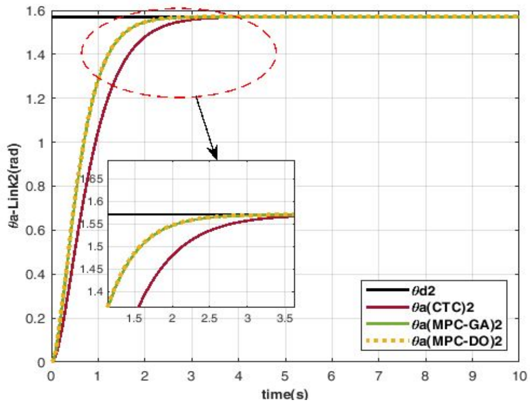

Figure 7. Performances of controllers for link 2

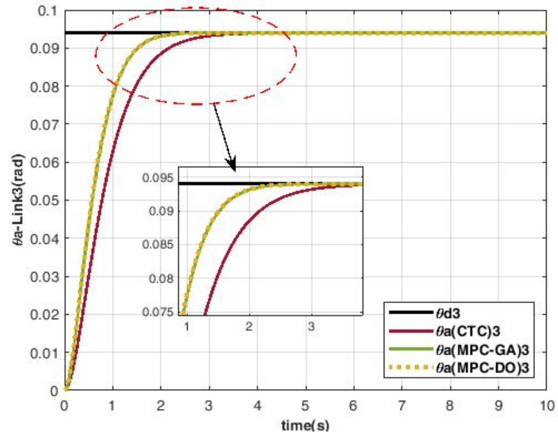

Figure 8. Performances of controllers for link 3

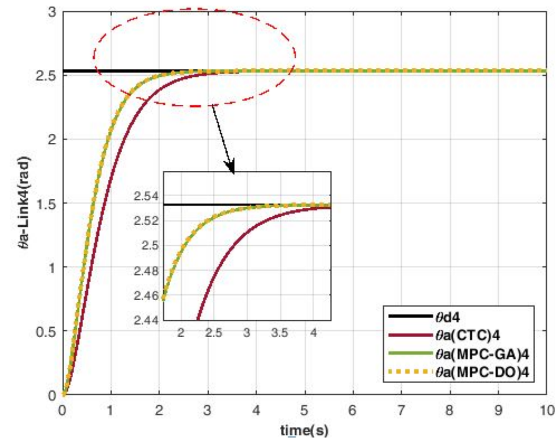

Figure 9. Performances of controllers for link 4

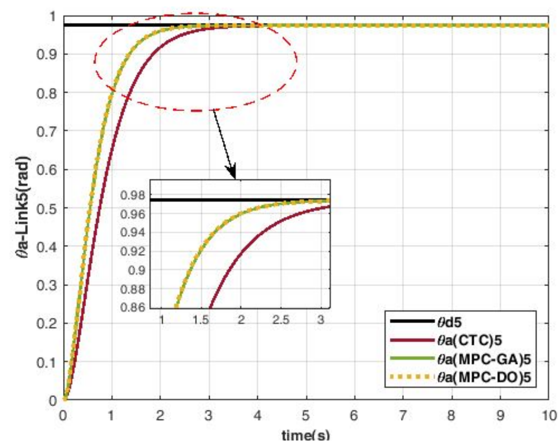

Figure 10. Performances of controllers for link 5

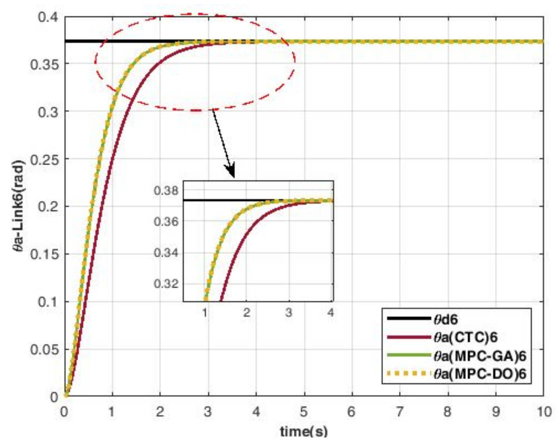

Figure 11. Performances of controllers for link 6

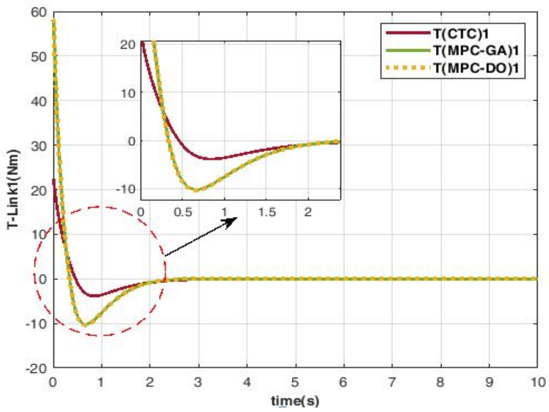

Figure 12. Torques for link 1

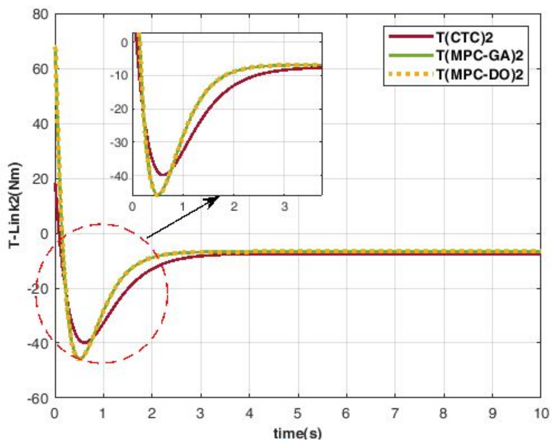

Figure 13. Torques for link 2

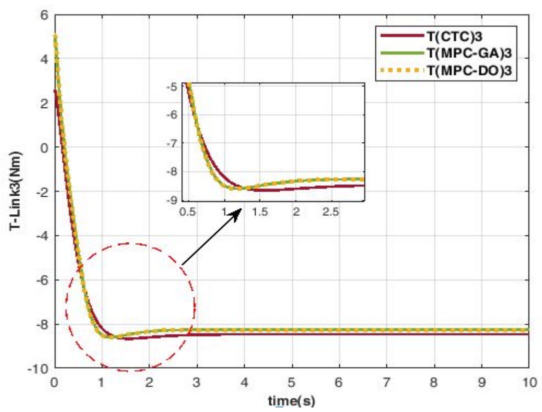

Figure 14. Torques for link 3

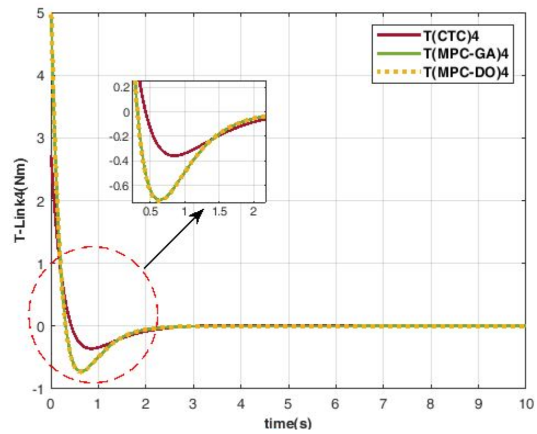

Figure 15. Torques for link 4

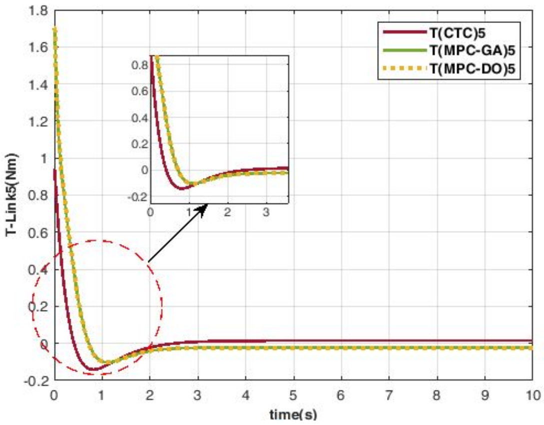

Figure 16. Torques for link 5

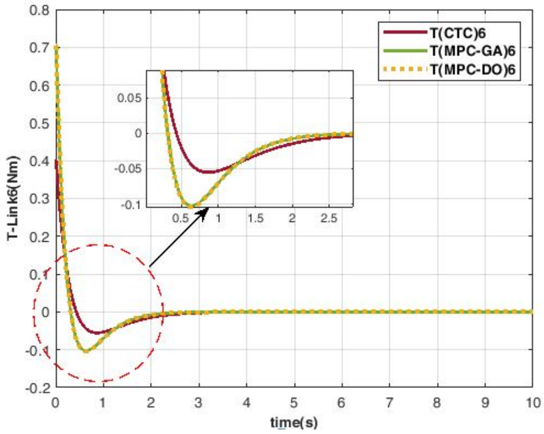

Figure 17. Torques for link 6

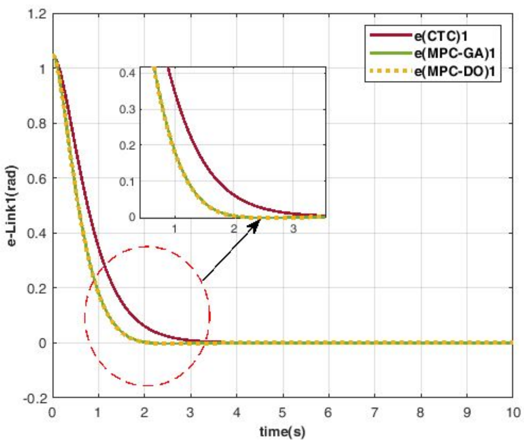

Figure 18. Errors for link 1

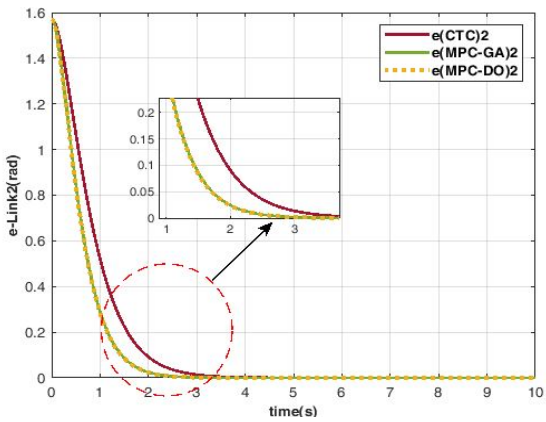

Figure 19. Errors for link 2

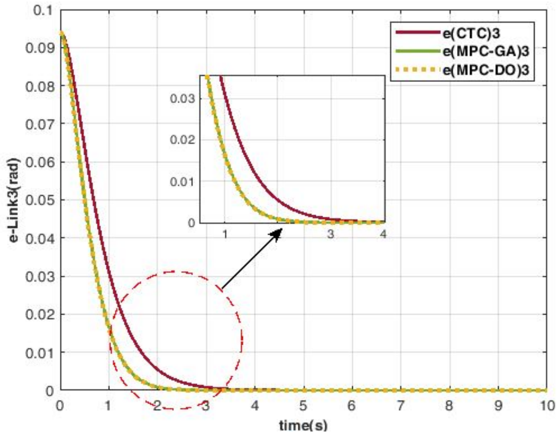

Figure 20. Errors for link 3

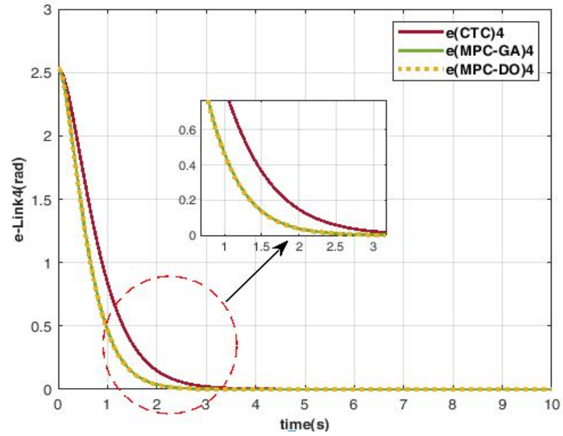

Figure 21. Errors for link 4

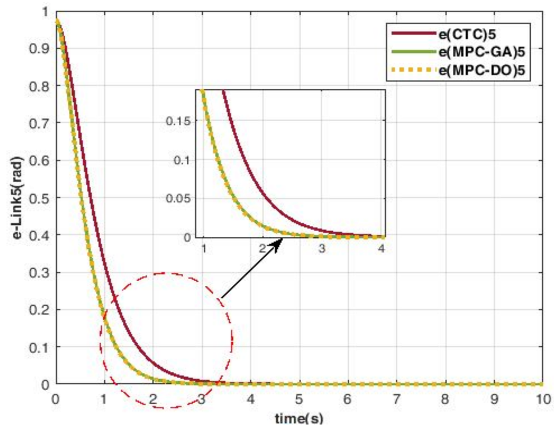

Figure 22. Errors for link 5

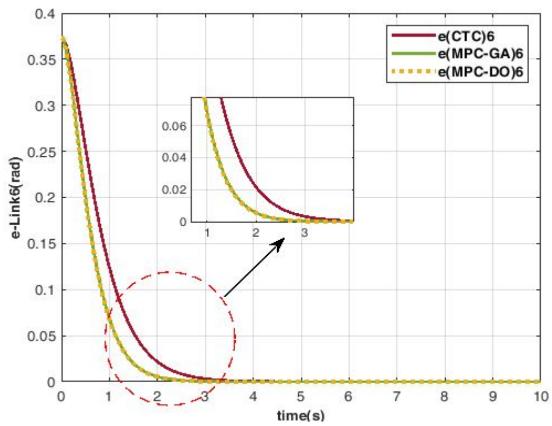

Figure 23. Errors for link 6

5. CONCLUSION

This study investigated the performance of CTC- based GA compared to MPC based - DO and GA for a six-DOF robot manipulator. These techniques involve linearizing a nonlinear dynamic model using feedback linearization. After that, based on the linear model, the CTC and MPC controllers have been developed. GA is used to tune the parameters k_p and k_d, while ω_0 and ζ are tuned by DO and GA to obtain the optimal values of k_1 and k_2. The results of the simulation display that the MPC- based DO controller reduces settling time and rising time compared to CTC- based GA and MPC-based GA while maintaining a better steady-state error across all links. The simulation results show that the MPC-based DO controller reduces settling time and rising time across all six links compared to both CTC-based GA and MPC-based GA, while maintaining better steady-state error across all links. The complexity of this research arises from the need to simultaneously handle the robot's highly nonlinear coupled dynamics, real-time computational constraints of the MPC optimization loop, and the use of two different tuning methods, DO and GA within a unified control framework. The recommendations for future works are summarized as to implement real time hardware experimental system for 6-DoF robotic system based on different controllers and optimization techniques.

REFERENCES

[1] Abadi, A. S. S., Ordys, A., Pierscionek, B.: Controlling a Teleoperated Robotic Eye Surgical System under a Communication Channel's Unknown Time Delay, in: *2023 27th International Conference on Methods and Models in Automation and Robotics (MMAR)*, IEEE, pp. 211–215, 2023.

[2] Soltani Sharif Abadi, A., Ordys, A., Kukielka, K., Pierscionek, B.: Review on Challenges for Robotic Eye Surgery; Surgical Systems, Technologies, Cost□effectiveness, and Controllers, The International Journal of Medical Robotics and Computer Assisted Surgery, Vol. 19 No.4, p. e2524, 2023.

[3] Yamazaki, K., Ueda, R., Nozawa, S., Kojima, M., Okada, K., Matsumoto, K., Ishikawa, M., Shimoyama, I., Inaba, M.: Home-Assistant Robot for an Aging Society, Proceedings of the IEEE, Vol. 100 No.8, pp. 2429–2441, 2012.

[4] Knop, L., Ziaeefard, S., Ribeiro, G. A., Page, B. R., Ficanha, E., Miller, M. H., Rastgaar, M., Mahmoudian, N.: A Human-Interactive Robotic Program for Middle School STEM Education, in: *2017 IEEE Frotiers in Education Conference (FIE)*, pp. 1–7, 2017.

[5] Trung, P. X., Quyen, P. T., Mai, T. T. T.: Development of an Intelligence Vision for a Robot System to Pick and Place Objects, FME Transactions, Vol. 53 No.2, pp. 233–242, 2025.

[6] Essa, M. E. S. M., Khalil, M. M., El-Beltagy, M. A.: Intelligent Improvement of Kalman Filter Based on Artificial Intelligence for Sensorless Speed Estimation and Control of DC Motors, FME Transactions, Vol. 53 No.4, pp. 525–536, 2025.

[7] Hussein, R. M.: Design a New Hybrid Controller Based on an Improvement Version of Grey Wolf Optimization for Trajectory Tracking of Wheeled Mobile Robot, FME Transactions, Vol. 51 No.2, pp. 140–148, 2023.

[8] Cong, V. D.: Design and Development of a Cost Efficiency Robot Arm with a PLC-Based Robot Controller, FME Transactions, Vol. 52 No.2, pp. 226–236, 2024.

[9] Li, Z.: Review of PID Control Design and Tuning Methods, Conf. Service - J. Physics, Vol. 2649 No.1, p. 012009, 2023.

[10] Jayaswal, K., Palwalia ,D. K., Kumar, S.: Performance Investigation of PID Controller in Trajectory Control of Two-Link Robotic Manipulator in Medical Robots, J. Interdisciplinary Mathematics, Vol. 24 No.2, pp. 467–478, 2021.

[11] Choubey, C., Ohri, J.: Tuning of LQR-PID Controller to Control Parallel Manipulator, Neural Computing & Applications, Vol. 34 No.4, pp. 3283–3297, 2022.

[12] Choubey, C., Ohri, J.: GWO-Based Tuning of LQR-PID Controller for a 3-DOF Parallel Manipulator, IETE - J. Research, Vol. 69 No.7, pp. 4378–4393, 2023.

[13] Abadi, A. S. S. et al.: Novel Off-Line Self-Tuning Controller with Guaranteed Stability, Int. J. Dynam. Control, Vol. 24 No.3, pp. 851–862, 2023.

[14] Tinoco, V., Silva, M. F., Santos, F. N., Morais, R., Magalhães, S. A., Oliveira, P. M.: A Review of Advanced Controller Methodologies for Robotic Manipulators, Int. J. Dynam. Control, Vol. 13 No.1, p. 36, 2025.

[15] Zheng, W., Chen, M.: Sliding Mode Tracking Control of a Two-Link Robotic Manipulator Using Nonlinear Disturbance Observer, in: *2017 4th International Conference on Information, Cybernetics and Computational Social Systems (ICCSS)*, pp. 192–197, 2017.

[16] Singh, S., Qureshi, M. S., Swarnkar, P.: Comparison of Conventional PID Controller with Sliding Mode Controller for a 2-Link Robotic Manipulator, in: *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, IEEE, pp. 115–119, 2016.

[17] Nadda, S., Swarup, A.: Integral Sliding Mode Control for Position Control of Robotic Manipulator, in: *2018 5th International Conference on Signal Processing and Integrated Networks (SPIN)*, IEEE, pp. 639–642, 2018.

[18] Chen, W., Xu, T., Liu, J., Wang, M., Zhao, D.: Picking Robot Visual Servo Control Based on Modified Fuzzy Neural Network Sliding Mode Algorithms, Electronics, Vol. 8 No.6, p. 605, 2019.

[19] Xue, P., Li, Q., Fu, G.: Design and Control Simulation Analysis of Tender Tea Bud Picking Manipulator, Applied Sciences, Vol. 14 No.2, p. 928, 2024.

[20] Rouhani, E., Erfanian, A.: A Finite-Time Adaptive Fuzzy Terminal Sliding Mode Control for Uncer–

tain Nonlinear Systems, Int. J. Control Autom. Syst., Vol. 16 No.4, pp. 1938–1950, 2018.

[21] Mary, A. H., Al-Talabi, A., Kara, T., Muneam, D. S., Almuhanna, M. Y., Mayyahi, L. A. K.: Adaptive Robust Tracking Control of Robotic Manipulator Based on SMC and Fuzzy Control Strategy, Al-Khwarizmi Engineering Journal, Vol. 20 No.1, pp. 63–75, 2024.

[22] Pan, Y., Yang, C., Pan, L., Yu, H.: Integral Sliding Mode Control: Performance, Modification, and Im–provement, IEEE Transactions on Industrial Informatics, Vol. 14 No.7, pp. 3087–3096, 2018.

[23] Abadi, A. S. S., Hosseinabadi, P. A.: Fuzzy Adap–tive Finite Time Control Ship Fin Stabilizing Sys–tems Model of Fuzzy Takagi-Sugeno with Unk–nowns and Disturbances, in: *2018 6th Iranian Joint Congress on Fuzzy and Intelligent Systems (CFIS)*, IEEE, pp. 33–36, 2018.

[24] Abadi, A. S. S., Hosseinabadi, P. A., Mekhilef, S.: Fuzzy Adaptive Fixed-Time Sliding Mode Control with State Observer for A Class of High-Order Mismatched Uncertain Systems, Int. J. Control Autom. Syst., Vol. 18 No.10, pp. 2492–2508, 2020.

[25] Liu, S., Wang, J., Zheng, Z.: Research on PMSM Speed Control System Based on Adaptive Fuzzy Control, Conf. Service - J. Physics, Vol. 1732 No.1, p. 012156, 2021.

[26] Zhilenkov, A., Chernyi, S., Firsov, A.: Autonomous Underwater Robot Fuzzy Motion Control System with Parametric Uncertainties, Designs, Vol. 5 No.1, p. 24, 2021.

[27] Benyezza, H., Bouhedda, M., Rebouh, S.: Zoning Irrigation Smart System Based on Fuzzy Control Technology and IoT for Water and Energy Saving, J. Cleaner Prod., Vol. 302, p. 127001, 2021.

[28] Hamdy, M., Magdy, M., Helmy, S.: Control and Synchronization for Two Chua Systems Based on Intuitionistic Fuzzy Control Scheme: A Comparative Study, Transactions of the Institute of Measurement and Control, Vol. 43 No.7, pp. 1650–1667, 2021.

[29] Torres-Pinzón, C. A., Paredes-Madrid, L., Flores-Bahamonde, F., Ramirez-Murillo, H.: LMI-Fuzzy Control Design for Non-Minimum Phase DC-DC Converters: An Application for Output Regulation, Applied Sciences, Vol. 11 No.5, p. 2286, 2021.

[30] Lin, G., Yu, J., Liu, J.: Adaptive Fuzzy Finite-Time Command Filtered Impedance Control for Robotic Manipulators, IEEE Access, Vol. 9, pp. 50917–50925, 2021.

[31] Feng, C., Chen, Z., Jin, W., Guo, W.: Motion Cont–rol and Simulation Analysis of a Manipulator Based on Computed Torque Control Method, in: *Inter–national Conference on Intelligent Robotics and Applications*, Springer Nature, Singapore, pp. 10–22, 2023.

[32] Ullah, M. I., Ajwad, S. A., Islam, R. U., Iqbal, U., Iqbal, J.: Modeling and Computed Torque Control of a 6 Degree of Freedom Robotic Arm, in: *2014 International Conference on Robotics and Eme–rging Allied Technologies in Engineering*, IEEE, pp. 133–138, 2014.

[33] Sancak, K. V., Bayraktaroglu, Z. Y.: Nonlinear Computed Torque Control of 6-Dof Parallel Mani–pulators, Int. J. Control Autom. Syst., Vol. 20 No.7, pp. 2297–2311, 2022.

[34] Şen, G. D., Öke Günel, G.: NARMA-L2–Based On–line Computed Torque Control for Robotic Manipu–lators, Transactions of the Institute of Measurement and Control, Vol. 45 No.13, pp. 2446–2458, 2023.

[35] Elmoushi, E. L., Hassan, H. A., Ayoub, N., Abdelwahab, S. A.: Dynamic modeling and com–puted torque control of a 5-dof manipulator robot considering friction, Journal of the Egyptian Soci–ety of Tribology, Vol. 22 No.1, pp. 122–163, 2025.

[36] Sangdani, M. H., Tavakolpour-Saleh, A. R., and Lotfavar, A.: Genetic Algorithm-Based Optimal Computed Torque Control of a Vision-Based Trac–ker Robot: Simulation and Experiment, Engineering Applications of Artificial Intelligence, Vol. 67, pp. 24–38, 2018.

[37] Schwenzer, M., Ay, M., Bergs, T., Abel, D.: Re–view on Model Predictive Control: An Engineering Perspective, Int. J. Advanced Manuf. Techno., Vol. 117 No.5, pp. 1327–1349, 2021.

[38] Santos, J. C., Gouttefarde, M., Chemori, A.: A No–nlinear Model Predictive Control for the Position Tracking of Cable-Driven Parallel Robots, IEEE Transactions on Robotics, Vol. 38 No.4, pp. 2597–2616, 2022.

[39] Chemori, A., Kouki, R., Bouani, F.: A New Fast Nonlinear Model Predictive Control of Parallel Manipulators: Design and Experiments, Control Engineering Practice, Vol. 130, p. 105367, 2023.

[40] Wu, H., Jin, S., Yin, C., Zheng, J., Hou, Z.: Model Free Adaptive Predictive Tracking Control for Ro–bot Manipulators with Uncertain Parameters, in: *2021 IEEE 10th Data Driven Control and Learning Systems Conference (DDCLS)*, pp. 1571–1576, 2021.

[41] Kleff, S., Meduri, A., Budhiraja, R., Mansard, N., Righetti, L.: High-Frequency Nonlinear Model Pre–dictive Control of a Manipulator, in: *2021 IEEE International Conference on Robotics and Automa–tion (ICRA)*, pp. 7330–7336, 2021.

[42] KUKA: LBR Iiwa 14 R820. Accessed: 2024-06-11 (N.D.).

[43] Lu, Y., Han, L., Liu, J., Li, S.: Model Predictive Tracking Control for Rigid Manipulators with Disturbance Rejection, in: *2022 41st Chinese Control Conference (CCC)*, pp. 2705–2710, 2022.

[44] Liu, Z., Lv, Z., Zheng, W., Wang, X.: Trajectory Control of Two-Degree-of-Freedom Sweet Potato Transplanting Robot Arm, IEEE Access, Vol. 10, pp. 26294–26306, 2022.

[45] Slavković, N., Živanović, S., Vorkapić, N., Dimić, Z.: Development of the Programming and Simu–lation System of 4-Axis Robot with Hybrid Kine–matic, FME Transactions, Vol. 50 No.3, pp. 403–411, 2022.

[46] Zhou, Y., Li, Z., Cui, J., Li, Y., Zhu, M.: Two-Level Variable Impedance Control for Internal/ External Forces Tracking of Dual-Arm Manipulators under Uncertainties, ISA Transactions, Vol. 167, pp. 899–913, 2025.

[47] Oleinikov, A., Soltan, S., Balgabekova, Z., Bemporad, A., Rubagotti, M.: Scenario-Based Model Predictive Control with Probabilistic Human Predictions for Human–Robot Coexistence, Control Engineering Practice, Vol. 142, p. 105769, 2024.

[48] Piltan, F., Emamzadeh, S., Hivand, Z., Shahriyari, F., Mirazaei, M.: PUMA-560 Robot Manipulator Position Sliding Mode Control Methods Using MATLAB/SIMULINK and Their Integration into Graduate/Undergraduate Nonlinear Control, Robotics and MATLAB Courses, Int. J. Robo. & Auto., Vol. 3, pp. 106–150, 2012.

[49] Poignet, P., Gautier, M.: Nonlinear Model Predictive Control of a Robot Manipulator, in: *6th International Workshop on Advanced Motion Control. Proceedings (Cat. No.00TH8494)*, IEEE, pp. 401–406, 2000.

[50] Feng, Y., Yu, X., Man, Z.: Non-Singular Terminal Sliding Mode Control of Rigid Manipulators, Automatica, Vol. 38 No.12, pp. 2159–2167, 2002.

[51] Uebel, M., Minis, I., Cleary, K.: Improved Computed Torque Control for Industrial Robots, IEEE Computer Society, pp. 528–533, 1992.

[52] Craig, J. J.: *Introduction to Robotics: Mechanics and Control, 3/E*, Pearson Education India, 2009.

[53] Lozano-Pérez, T., Mason, M. T., Taylor, R. H.: Automatic Synthesis of Fine-Motion Strategies for Robots, The International Journal of Robotics Research, Vol. 3 No.1, pp. 3–24, 1984.

[54] Al Ashi, M.: Trajectory Tracking Control of A 2-DOF Robot Arm Using Neural Networks, 2014.

[55] Jazar, R. N.: *Theory of Applied Robotics*, Springer Science+ Business Media, LLC, 2010.

[56] Lewis, F. L., Dawson, D. M., Abdallah, C. T.: *Robot Manipulator Control: Theory and Practice*, CRC Press, 2003.

[57] khalil, H. K., Grizzle, J. W.: *Nonlinear Systems*, Prentice hall Upper Saddle River, NJ, 2002.

[58] Piltan, F., Yarmahmoudi, M., Mirzaie, M., Emamzadeh, S., Hivand, Z.: Design Novel Fuzzy Robust Feedback Linearization Control with Application to Robot Manipulator, International Journal of Intelligent Systems and Applications, Vol. 5 No.5, p. 1, 2013.

[59] Guechi, E. H., Bouzoualegh, S., Zennir, Y., Blažič, S.: MPC Control and LQ Optimal Control of A Two-Link Robot Arm: A Comparative Study, Machines, Vol. 6 No.3, p. 37, 2018.

[60] Magni, L., Scattolini, R., Åström, K. J.: Global Stabilization of the Inverted Pendulum Using Model Predictive Control, IFAC Proceedings Volumes, Vol. 35 No.1, pp. 141–146, 2002.

[61] Gawthrop, P. J., Wang, L.: Intermittent Predictive Control of an Inverted Pendulum, Control Engineering Practice, Vol. 14 No.11, pp. 1347–1356, 2006.

[62] Mills, A., Wills, A., Ninness, B.: Nonlinear Model Predictive Control of an Inverted Pendulum, in: *2009 American Control Conference*, IEEE, pp. 2335–2340, 2009.

[63] Guechi, E. H., Bouzoualegh, S., Messikh, L., Blažic, S.: Model Predictive Control of a Two-Link Robot Arm, in: *2018 International Conference on Advanced Systems and Electric Technologies (IC_ASET)*, IEEE, pp. 409–414, 2018.

[64] Murray, R. M., Li, Z., Sastry, S. S.: *A Mathematical Introduction to Robotic Manipulation*, CRC Press, 2017.

[65] Spong, M. W., Vidyasagar, M.: *Robot Dynamics and Control*, John Wiley & Sons, 2008.

[66] Siciliano, B., Khatib, O., and Kröger, T.: *Springer Handbook of Robotics*, Springer, 2008.

NOMENCLATURE

L	Lagrangian
K	Kinetic energy
P	Potential energy
θ_i	Joint-variable vector
τ_i	General nonpotential force
$\theta, \dot{\theta}$ and $\ddot{\theta}$	6×1 vectors of generalized joint coordinates respectively (Position, velocities and accelerations)
M	6×6 inertia matrix of joint space
N	6×1 the vector of nonlinearity term
τ	6×1 torque vector at the robot joints
k_p	Proportional gain
k_d	Derivative gain
v	Synthetic control vector
C	6×6 Coriolis and centripetal coupling matrix
G	Gravity loading 6×1 vector
ω_0	Natural frequency
ζ	Damping ratio
h	prediction horizon time
ρ	Weight factor
i_L	Inductor current
I_P	Photogenerated current of the PV cell
I_{SC}	Short-circuit current of the PV cell
k1 and k2	Second-order system's behavior
θ_{1d}	Reference angle of the first link
$e_1(t+h)$	Predicted angle error
$\dot{e}_1(t+h)$	Predicted velocity error
J	Quadratic cost function
N	Number of search agents

Acronyms and abbreviations

MPC	Model Predictive Control
CTC	Computed Torque Control
DO	Dandelion Optimization
GA	Genetic Algorithm
SSE	Steady-State Error
DOF	Degree-Of-Freedom
PID	proportional-integral-derivative

LQR	linear quadratic regulator
SMC	sliding mode control
PMSM	Permanent Magnet Synchronous Motor
IOT	Internet of Things
DDP	differential dynamic programming
GPIO	generalized proportional-integral observer
L-E	LAGRANGE-EULER
LHS	Left hand side
LB	lower bound
UB	upper bound
OS	Overshoot
e	error

ДИНАМИЧКО ПРЕДИКТИВНО УПРАВЉАЊЕ ЗАСНОВАНО НА ОПТИМИЗАЦИЈИ МАСЛАЧКА ЗА ПРЕЦИЗНО ПРАЋЕЊЕ РОБОТСКОГ МАНИПУЛАТОРА СА 6 СТЕПЕНИ СЛОБОДЕ

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Овај рад предлаже оптимизоване стратегије управ–љања за динамички роботски манипулатор са 6 веза коришћењем предиктивног управљања моделом (MPC) и традиционалног рачунарског управљања обртним моментом (CTC). За подешавање MPC контролера користе се две методе оптимизације, наиме оптимизација маслачка (DO) заснована на MPC и генетски алгоритам (GA) заснован на MPC. Стратегије су процењене у смислу индекса перфор–манси заснованих на временском домену, времену смиривања, времену пораста, проценту прекорачења и грешци у стационарном стању (SSE). Резултати симулације су показали да традиционални CTC пати од већег напора управљања и споријег прелазног одзива, углавном за везе високог реда. Насупрот томе, стратегија управљања заснована на MPC зна–чајно побољшава динамичке перформансе и тачност праћења. Међу тестираним приступима, DO засно–ван на MPC постиже минимално преко–рачење, глађе профиле обртног момента, најбржу конвер–генцију и најнижу SSE на свих шест роботских веза. Добијени резултати у MATLAB/ SIMULINK-у пот–врђују и доказују да оптимизовани MPC контролер, посебно DO базиран на MPC-у, нуди ефикасно и робусно решење за управљање роботским манипулаторима са високим степеном слободе.