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Energy-Efficient Trajectory Tracking of a 2-DOF Planar Manipulator Using Optimized Computed Torque Control

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Abstract: This study presents an optimisation-based control strategy for improving the energy efficiency of robotic manipulators without compromising motion accuracy. A two-degree-of-freedom (2-DOF) planar manipulator is modeled using the Euler–Lagrange formulation to capture its nonlinear dynamic behavior [1]. The control architecture employs the standard Computed Torque Control (CTC) method, which linearizes the nonlinear dynamics through model-based compensation. Unlike conventional fixed or high-gain tuning approaches that often result in excessive torque demand and increased energy consumption, the proposed approach adopts an optimal CTC framework. Within this framework, the proportional and derivative gains are determined through a constrained nonlinear optimization process that minimizes the integral of squared joint torques—defined as the energy cost function—while ensuring the trajectory tracking error remains within a predefined tolerance. The nonlinear optimization is implemented in MATLAB using a simulation-based iterative procedure, where the system dynamics are embedded within each optimization cycle. The resulting optimized controller demonstrates a significant reduction in actuator effort and overall energy expenditure compared to the conventional CTC method. Although not universally optimal, gain-optimized controllers present a practical and effective means for achieving energy-efficient robotic motion control.
Keywords: Energy-efficient control, computed torque controller, nonlinear optimization, robotic manipulator, trajectory tracking, Euler–Lagrange dynamics, MATLAB simulation.

I. INTRODUCTION

The growing integration of robotic manipulators across industrial manufacturing, logistics, and service domains has further increased the need for systems that are not only accurate and responsive but also energy-efficient. Traditional performance metrics in robotic control, such as high-speed motion and precise trajectory tracking, have long dominated controller design philosophies. However, the continuous operation of actuated robotic systems introduces substantial energy and maintenance costs, mainly driven by excessive torque generation and frequent high-magnitude actuation. Since actuator power dissipation and mechanical wear are both directly related to the amplitude and frequency of applied torques, improving energy efficiency has become a key factor for the sustainable design of robotic systems. Among the various control techniques, Computed Torque (CTC) has emerged as one of the most effective model-based approaches for accurate motion tracking in nonlinear robotic systems [2]. By compensating for the manipulator's inherent nonlinearities—represented by the inertia matrix $M(q)$, Coriolis and centrifugal effects $C(q, \dot{q})\dot{q}$, and gravitational torques $G(q)$—CTC effectively linearizes and decouples the system dynamics. This transformation allows the closed-loop system to act like a set of independent linear second-order systems governed by the proportional and derivative control gains, Kp and Kd. In practice, these gains are tuned to achieve rapid response and minimum tracking error, often with heuristic or frequency-domain methods that focus exclusively on dynamic performance criteria. While such tuning methods result in very accurate tracking, they usually do not consider the energetic implications of aggressive control action: high gain values imply stiff system responses and sharp torque transients, correspondingly increasing power consumption, actuator heating, and mechanical stress. In general, there is a natural trade-off between tracking accuracy and energy efficiency, and such issues have remained largely unexplored by many classical control studies. Focusing on this specific methodological gap, the current work presents an optimization-based method that systematically refines controller gains to find a good balance between tracking precision and energy consumption. This study proposes, develops, and validates an Optimized Computed Torque Control framework for a two-degree-of-freedom (2-DOF) planar manipulator. The proposed method identifies the optimal set of constant Kp and Kd gains that minimize the total actuation energy, expressed as the integral of squared joint torques, while maintaining the trajectory tracking error within an allowable tolerance [3]. This approach is based on a classical CTC formulation combined with a constrained nonlinear optimization routine; the optimization cost function represents energy expenditure, while the constraint enforces tracking accuracy.

First, the nonlinear dynamic model of a 2-DOF planar manipulator has been derived using the Euler-Lagrange formulation, laying a rigorous basis for model-based control. Second, a constrained optimization framework is proposed to link controller gains directly to closed-loop performance metrics, enabling automated energy-tuned control parameter selection. Finally, a comparative simulation study quantifies significant energy savings, represented in terms of the torque energy integral, without loss in trajectory tracking fidelity for the optimized controller. These results emphasize the role that optimization-based control design can play in enhancing the energy efficiency of robotic manipulators—a keystone in achieving sustainable and intelligent robotic systems.

II. BACKGROUND AND PRIOR RESEARCH

A. Canonical Computed Torque Control and Practical Considerations

The Computed Torque Control concept is derived from the application of the method of feedback linearization to nonlinear robotic systems. Since the complex, coupled robot dynamics are effectively transformed into a set of linear, decoupled mass-unit systems by explicitly calculating and compensating for the inertial, Coriolis, centrifugal, and gravitational forces, the subsequent control design can be done in a straightforward manner [4]. Standard linear controllers, typically a Proportional-Derivative (PD) loop, will then ensure stability for this linearized system, which in turn determines the auxiliary acceleration command based upon tracking error and its derivative.

However, the effectiveness of CTC inherently depends on perfect model knowledge. In realistic scenarios, the presence of joint friction, external disturbances, and varying payload introduces parametric uncertainties that can significantly affect the performance of inverse dynamics compensation. Hence, in practice, research efforts have focused on either adaptive control or self-tuning algorithms to update gains depending on manipulator state or observed tracking errors, based on more realistic assumptions of actuator torque limitations and model inaccuracies. Building on these, our work adds the use of systematic optimization in selecting gains, with less focus on fundamental stability or robustness of the control architecture and greater emphasis on operational efficiency dictated by energy cost.

B. Energy Minimization Techniques in Robot Control

Minimizing energy consumption in robotics typically falls into two main categories: optimal trajectory planning and optimal control implementation. In optimal control theory, the system energy dissipation is frequently modeled by the objective function . This metric serves as an effective proxy for electrical energy consumption, particularly for DC motors where torque is proportional to current , and heat loss dominates power dissipation. Minimizing the integral of the squared torque naturally favors solutions that smooth out control effort and avoid high peak forces, which contribute disproportionately to the overall energy cost [5].

Many studies focus on optimizing the trajectory itself, often by tuning the coefficients of high-order polynomials (such as quartic or quintic functions) or by minimizing the total execution time , subject to actuator and path constraints. While trajectory optimization is powerful, it mandates a separate planning stage for every task. In contrast, this study focuses on optimizing the *controller gains* for a fixed, required trajectory. This approach offers a distinct advantage: once optimized, the resulting gain set represents the most energy-efficient closed-loop stiffness that meets performance requirements, offering a more generally applicable solution for dynamic control regardless of the specific trajectory geometry, as long as it adheres to the initial assumptions

C. Trajectory Planning and Optimization Tools

The quality of the reference trajectory has a considerable direct effect on the control effort needed. In order to minimize unnecessary high-frequency dynamics, the use of a smooth trajectory is important. We utilize quintic polynomial interpolation, which allows us to set boundary conditions on not only position and velocity but also acceleration (and implicitly jerk) at the start and end points [6]. Setting zero initial and final acceleration (and thus zero jerk), ensures a torque profile that is smooth and limits substantial spikes in overall required torque, which supports the final outcome of energy efficiency.

To address the significantly more complicated, coupled minimization problem from simulation, a robust numerical optimization solution. As such, we employ MATLAB's fmincon solver for which is designed to do constrained nonlinear optimization. The fmincon function can address an objective function to be minimized, and provide for the nonlinear constraints imposed by the use of complex dynamic simulations used in the overall work. The optimization requires that the full robot dynamics (determined via an ODE solver) be embedded in the objective and constraint evaluation function. To limit computation time in construction of the full simulation of the robot dynamics, and thereby avoid additional computations, structures such as using nested functions can allow for the intermediate values (in this case, the full trajectory simulation) to be recalled for both the objective and the constraints.

III. DYNAMIC MODELLING OF THE 2-DOF PLANAR MANIPULATOR

A. *Physical Configuration and Parameters*

The system under study is a standard 2-DOF planar (RR) manipulator, consisting of two rigid links connected by two revolute joints. The motion is restricted to the horizontal plane. This configuration allows for the assumption that the gravitational effects are negligible or completely compensated for by the base structure, leading to . The joint space coordinates are defined by , representing the angles of the two links relative to the base frame.

The dynamic model is highly dependent on the physical properties of the links. For reproducibility and simulation fidelity, the standard parameters used for the modeling and simulation are provided below.

Table 1 - Physical Parameters Of The Manipulator

Parameter	Symbol	Value	Unit
Link 1 length	L_1	1.0	m
Link 2 length	L_2	1.0	m
Link 1 mass	m_1	5.0	kg
Link 2 mass	m_2	2.0	kg
C.M. distances	l_{c1}, l_{c2}	0.5	m
Moments of inertia	I_1, I_2	$mL^2/12$	kg·m²
Gravity	g	0	m/s²
Simulation time	T_{sim}	5.0	s
Time step	dt	0.005	s

B. *Lagrangian Formulation and Derivation*

The dynamic equations of motion are rigorously derived using the Euler-Lagrange method, which relies on the system's energy description and provides a systematic pathway for complex mechanical systems [7]. The method utilizes the Lagrangian, L=K-P, where K is the total kinetic energy and P is the total potential energy.

The generalized dynamic equation is given by:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = \tau_i, \quad i = 1,2$$

Since the manipulator is planar and operating horizontally, the potential energy P is constant (or zero, relative to the horizontal plane), meaning G(q)=0. Therefore, the Lagrangian simplifies to L=K , the total kinetic energy of the system. The kinetic energy is the sum of the kinetic energy contributions from both links, accounting for both translation and rotation:

$$K = \frac{1}{2}m_1 v_{c1}^{T} v_{c1} + \frac{1}{2}I_1\dot{\theta}_1^2 + \frac{1}{2}m_2 v_{c2}^{T} v_{c2} + \frac{1}{2}I_2\left(\dot{\theta}_1 + \dot{\theta}_2\right)^2$$

Where V_{c1} and V_{C2} are the linear velocities of the centers of mass (C.M.) of Link 1 and Link 2, respectively. The derivation of these velocities in joint space leads to the final dynamic model in the standard form:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} = \tau$$

The inversion of this dynamics equation forms the crucial compensation component of the Computed Torque Controller.

C. *Explicit Dynamic Matrices*

The mass matrix $M(q)$ encapsulates the configuration-dependent inertial properties of the manipulator, while the Coriolis and centrifugal matrix $C(q,\dot{q})$ represents the velocity-dependent coupling forces arising from joint interaction. Accurate modelling of these matrices is crucial for achieving high-fidelity inverse dynamics compensation in the Computed Torque Control (CTC) scheme. Neglecting these nonlinear effects can lead to residual coupling, degraded tracking accuracy, and unnecessary energy consumption.

For a two-degree-of-freedom (2-DOF) planar manipulator, the components of the mass matrix are derived from the link kinetic energies as follows:

$$M(q) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

where

$$M_{11} = m_1 l_{c1}^2 + I_1 + m_2(L_1^2 + l_{c2}^2 + 2L_1 l_{c2}\cos\theta_2) + I_2,$$
$$M_{12} = m_2(l_{c2}^2 + L_1 l_{c2}\cos\theta_2) + I_2,$$
$$M_{21} = M_{12},$$
$$M_{22} = m_2 l_{c2}^2 + I_2.$$

Here, L_1 represents the length of the first link, l_{c1} and l_{c2} are the distances from the respective joint axes to the centers of mass of links 1 and 2, I_1 and I_2 denote the link inertias about their centers of mass, and m_1 and m_2 are the link masses.

The Coriolis and centrifugal effects arise due to joint motion coupling and are formulated using Christoffel symbols of the first kind. Defining the coupling term h as

$$h = -m_2 L_1 l_{c2} \sin\theta_2,$$

the Coriolis and centrifugal matrix can be expressed as:

$$C(q,\dot{q}) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$$

with elements defined by:

$$C_{11} = h\dot{\theta}_2$$
$$C_{12} = h(\dot{\theta}_1 + \dot{\theta}_2)$$
$$C_{21} = -h\dot{\theta}_1$$
$$C_{22} = 0$$

The derived expressions highlight how the nonlinear inertial coupling depends simultaneously on the manipulator's configuration (θ_2) and joint velocities $(\dot{\theta}_1, \dot{\theta}_2)$. These terms become increasingly significant during high-speed motion, where small modeling errors can lead to large dynamic torque deviations. For the planar configuration considered in this work, gravitational effects are negligible ($G(q) = 0$), simplifying the dynamic model and focusing the control and optimization analysis purely on the velocity- and configuration-dependent nonlinearities represented by $M(q)$ and $C(q,\dot{q})$. This formulation serves as the foundation for implementing the inverse dynamics-based Computed Torque Controller.

IV. NOMINAL COMPUTED TORQUE CONTROLLER DESIGN

The Computed Torque Control (CTC) method is a model-based control technique that allows for bilinear and decoupled closed-loop motion through the use of explicit knowledge of the manipulator dynamics. The success of the CTC, however, is highly dependent on accurate system modeling and the generation of smooth reference trajectories. For the comparison and optimization baseline, we describe the nominal CTC formulation of the 2-DOF planar manipulator applied to the desired configuration.

A smooth reference trajectory is essential to guarantee finite actuator torque while ensuring continuous motion. Sudden changes in acceleration cause discontinuities in the torque demand of the actuators, creating unrealistic torque spikes that obscure the true influence of gain optimization on energy consumption. Therefore, we utilize a quintic polynomial trajectory for each joint to guarantee continuity of position, velocity, and acceleration throughout motion, as well as zero jerk at the endpoints of the motion. The desired joint trajectory is expressed as follows:

$$\theta_d(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$$

The six coefficients a_0 through a_5 are determined by applying boundary conditions on position, velocity, and acceleration at the initial and final times. For this study, each joint performs a specified movement within a total duration of $T = 5.0$ s. The trajectory parameters for both joints are:

Table 2 - Trajectory Parameters

Joint	$q(0)$(rad)	$\dot{q}(0)$(rad/s)	$\ddot{q}(0)$(rad/s²)	$q(T)$(rad)	T(s)
θ_1	0	0	0	$\pi/2$	5.0
θ_2	0	0	0	$-\pi/4$	5.0

The trajectory generator outputs the desired joint position $q_d(t)$, velocity $\dot{q}_d(t)$, and acceleration $\ddot{q}_d(t)$, which are used in the feedforward component of the control law.
The torque command required to produce the desired motion is computed by inverting the manipulator dynamics. Neglecting gravitational effects ($G(q) = 0$) for the planar case, the inverse dynamics model gives:

$$\tau = M(q)u + C(q, \dot{q})\dot{q}$$

Here, $u$denotes the auxiliary control input vector, which shapes the closed-loop tracking response. It is defined using a proportional-derivative (PD) law with a feedforward term:

$$u = \ddot{q}_d - K_v\dot{e} - K_p e$$

where $e = q - q_d$is the position error vector and $\dot{e} = \dot{q} - \dot{q}_d$is the velocity error.
For simplicity and to focus the optimization process on energy efficiency rather than inter-joint coupling, the gain matrices are taken as diagonal and uniform across both joints:

$$K_p = K_p I, K_v = K_v I$$

Thus, the design vector for optimization is $x = [K_p, K_v]^T$.
Substituting the above control law into the manipulator's dynamic equation gives the closed-loop error dynamics:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} = M(q)(\ddot{q}_d - K_v\dot{e} - K_p e) + C(q, \dot{q})\dot{q}$$

Under the assumption of a perfect dynamic model compensation ($M(q)$ and $C(q, \dot{q})$exactly known), this reduces to a fully linear and decoupled system:

$$\ddot{q} = \ddot{q}_d - K_v\dot{e} - K_p e$$

which, in terms of error variables, becomes:

$$\ddot{e} + K_v\dot{e} + K_p e = 0$$

This represents a standard second-order homogeneous system where $K_p$determines stiffness (responsiveness) and K_v represents damping (overshoot control). The design of these gains directly influences the balance between tracking precision and control effort.
For establishing a nominal high-performance baseline, the gains are selected using classical control relationships between the natural frequency $\omega_n$and damping ratio ζ [8]:

$$K_p = \omega_n^2, K_v = 2\zeta\omega_n$$

By choosing $\omega_n = 10$ rad/s and $\zeta = 1$, the resulting nominal gains are $K_{p,nom} = 100$and $K_{v,nom} = 20$. This tuning ensures fast, critically damped response but requires high actuator torque. It therefore serves as the reference configuration against which the optimized energy-efficient control strategy will be compared.

V. ENERGY OPTIMIZATION FORMULATION

The central objective of this work is an energy-efficient configuration of the Computed Torque Controller (CTC) without compromising trajectory tracking accuracy. This is realized under a constrained nonlinear optimization framework that systematically searches the controller gain space $x = [K_p, K_v]^T$to minimize the energy expenditure while sustaining precision motion tracking. The resulting controller ensures that both the control effort and tracking performance remain within practical engineering limits and hence provides an optimum balance between efficiency and accuracy.
To quantify the energy consumption due to a given control configuration, an energy cost function is developed based on the integral of the squared joint torque magnitude over the trajectory execution time. This captures the overall work performed by actuators during the entire motion and serves as an effective indicator of energy consumption. Mathematically, the cost function is expressed as:

$$J(x) = \int_0^T \tau^T(t)\tau(t)\, dt$$

where $\tau(t)$ is the instantaneous joint torque vector and $x = [K_p, K_v]^T$ represents the optimization variable set including the proportional and derivative gains, respectively. Minimizing $J(x)$ penalizes high as well as rapidly fluctuating torques, thereby promoting smoother and energetically efficient motion profiles. This formulation naturally avoids control strategies exhibiting large transient spikes or discontinuities in torque, which typically lead to energy losses and actuator wear.

However, reducing controller gains to minimize torque effort generally deteriorates tracking accuracy, as lower stiffness allows larger position deviations from the reference. To preserve high-precision operation, a constraint is imposed on the maximum instantaneous position error $E_{\max}(x)$, observed during simulation:

$$E_{\max}(x) = \max_{t\in[0,T]} \| e(t) \|_2$$

where $e(t) = q(t) - q_d(t)$ is the instantaneous position tracking error. For practical accuracy, this error should not exceed a predefined tolerance δ. In this work, a strict limit of $\delta = 5 \times 10^{-3}$ radians (approximately 0.286°) is imposed. The tracking constraint is added to the optimization as a nonlinear inequality constraint:

$$c(x) = E_{\max}(x) - \delta \leq 0$$

This constraint ensures that only gain combinations yielding acceptable tracking accuracy are considered feasible solutions. The optimization is solved using MATLAB's fmincon solver, which guarantees constraint satisfaction through an interior-point algorithm, ensuring that the optimized gains maintain physical feasibility and system stability [9].

The complete optimization problem is thus expressed as:

$$\begin{aligned} \min_{x\in\mathbb{R}^2} \quad & J(x) = \int_0^T \tau^T(t)\tau(t)\,dt \\ \text{subject to:} \quad & c(x) = E_{\max}(x) - \delta \leq 0, \\ & x_{lb} \leq x \leq x_{ub} \end{aligned}$$

where $x_{lb} = [1,1]^T$ and $x_{ub} = [200,50]^T$ define the lower and upper bounds on the gains. These bounds ensure the physical realism of the solution space by maintaining positive-definite gain values for stability and avoiding excessively large torques that could lead to actuator saturation or instability.

For any given gain vector x, the optimizer evaluates both the objective and constraint functions by fully simulating the time-domain closed-loop dynamics derived in Section IV. By numerically integrating the manipulator's dynamic equations over the trajectory duration, both the torque vector $\tau(t)$ and the resulting error trajectory $e(t)$ are computed. From this simulation, both the energy cost $J(x)$ and the maximum error $E_{\max}(x)$ are extracted. A single integrated function structure is implemented in MATLAB for computational efficiency, where both quantities are obtained within one simulation loop. This approach allows a single run of the ODE solver per iteration, significantly accelerating the convergence of the nonlinear optimization routine.

With this formulation, the optimization process yields an optimized CTC that minimizes energy expenditure while rigorously maintaining trajectory accuracy within the defined tolerance band. Results demonstrate that intelligent tuning of controller gains can achieve a substantial reduction in actuator effort, providing a sustainable and efficient control strategy for robotic manipulators.

VI. IMPLEMENTATION

The proposed control and optimization framework was implemented in MATLAB using numerical simulation of the 2-DOF planar manipulator. The simulation environment was configured to perform both dynamic integration and energy-based optimization under identical reference trajectories for a fair comparison between the nominal and optimized Computed Torque Controllers (CTC). The manipulator was modeled with link lengths $L_1 = L_2 = 1$ m and link masses $m_1 = 5$ kg and $m_2 = 2$ kg. The centers of mass were located at $l_{c1} = l_{c2} = 0.5$ m, and the moments of inertia were computed as $I_1 = m_1 L_1^2/12$ and $I_2 = m_2 L_2^2/12$. Gravitational effects were neglected ($g = 0$) to emulate horizontal-plane motion. Table 1 summarizes the parameters used in the simulation.

The manipulator was commanded to follow a quintic polynomial trajectory, ensuring zero velocity and acceleration at both endpoints for smooth motion. The desired angular displacements were defined as $q_1: 0 \to \frac{\pi}{2}$ rad and $q_2: 0 \to -\frac{\pi}{4}$ rad over a duration of five seconds. Velocities and accelerations were obtained by numerical differentiation of the reference profiles.

Two CTC configurations were tested:

- Nominal controller: $K_p = 150$, $K_v = 30$, representing a high-gain, fast-response design.
- Optimized controller: $K_p = 40$, $K_v = 8$, representing an energy-aware low-gain configuration obtained through constrained optimization.

The dynamic equations were integrated using an explicit Euler method with a time step of 5×10^{-3} s. Each iteration computed the joint torques using the inverse-dynamics law

$$\tau = \mathrm{M(q)\,u + C(q,\dot{q})\dot{q}}$$

Where

$$\mathrm{u} = \ddot{\mathrm{q}}_d - K_v(\dot{\mathrm{q}} - \dot{\mathrm{q}}_d) - K_p(\mathrm{q} - \mathrm{q}_d).$$

The manipulator acceleration was then computed as

$$\ddot{\mathrm{q}} = \mathrm{M}^{-1}(\mathrm{q})\,[\,\tau - \mathrm{C(q,\dot{q})\dot{q}}\,]$$

and integrated forward in time. The adaptive ODE45 solver was used in preliminary validation to verify the correctness of the dynamic model; however, fixed-step Euler integration was adopted in the main runs for consistency with the optimization process and faster computation.

The energy cost was evaluated as the cumulative integral of squared joint torques:

$$E(t) = \int_0^{\mathrm{T}} \tau^{\mathrm{T}}(\xi)\tau(\xi)\,d\xi$$

providing a direct measure of the actuator effort. The final energy values E_{nom} and E_{opt} were compared to quantify efficiency gains achieved by the optimized gains. All simulations were executed on a standard workstation. The optimization employed MATLAB's fmincon solver with an interior-point algorithm, function and constraint tolerances of 10^{-6}, and initial gains set to the nominal values. The solver iteratively called the dynamic simulation for each test vector $\mathrm{x} = [K_p, K_v]^T$, evaluating both the energy cost $J(\mathrm{x})$ and the nonlinear tracking-error constraint $E_{\max}(\mathrm{x}) \leq \delta$.

Three quantitative metrics were used for evaluation:

1) Total energy cost (J): Integral of squared torque, representing energy expenditure.
2) Maximum tracking error (E_max): Highest instantaneous deviation from the reference trajectory.
3) Peak torque (τ_peak): Maximum absolute joint torque, indicating actuator stress.

Visualization of results included joint position tracking, torque profiles, cumulative energy plots, and an animation of the manipulator motion for both controllers. The optimized controller consistently demonstrated smoother torque curves, reduced peak torque, and substantially lower cumulative energy compared to the nominal case while maintaining accurate trajectory tracking.

VII. RESULTS AND DISCUSSIONS

The MATLAB simulations on the 2-DOF planar manipulator model were used to compare the performance of the optimized Computed Torque Controller (O-CTC) and the nominal Computed Torque Controller (CTC). To illustrate the advantages of gain optimization over traditional high-gain tuning, the evaluation focuses on torque characteristics, energy efficiency, tracking performance, and actuator load profiles.

A. Torque Response Analysis

The torque profiles of both manipulator joints under nominal and optimal control configurations are shown in Figure 1. The torque signals in the nominal case show clear transient peaks during the acceleration phase, with values for Joint 1 and Joint 2 reaching roughly 10 and 2 Nm, respectively. The aggressive proportional and derivative gains that enforce fast tracking are the cause of these high peaks, which lead to excessive actuator

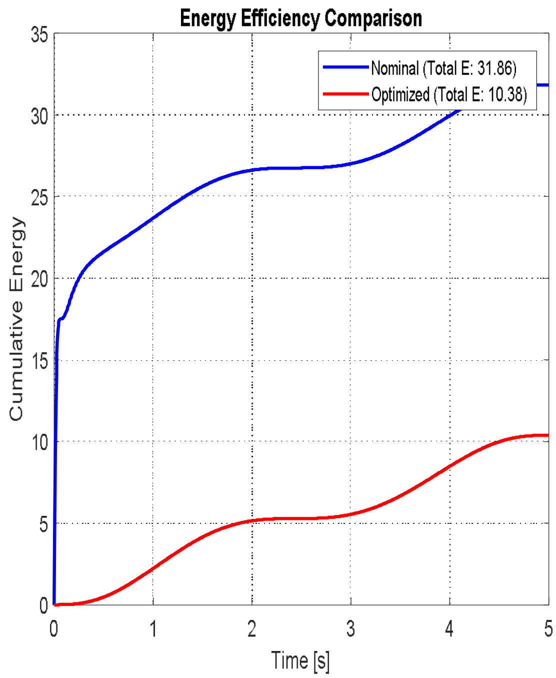
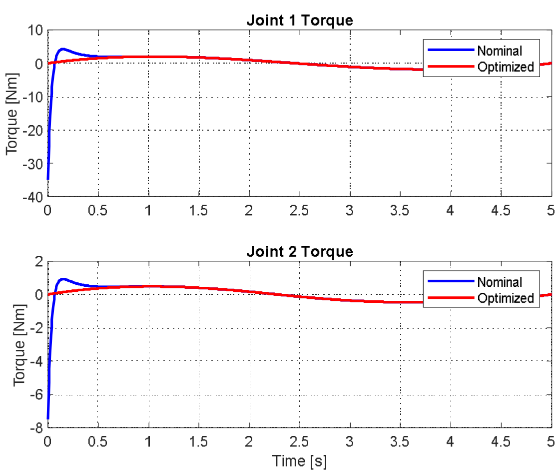


Figure 1 - Torque Response Analysis

activity and power dissipation. The optimized controller, on the other hand, results in noticeably smoother torque responses with much smaller oscillations and peak amplitudes. The steady-state torques closely match those of the nominal case, despite a slightly delayed settling in the transient phase. Without sacrificing motion accuracy, this significant torque magnitude reduction translates directly into less actuator effort, less mechanical stress, and increased overall energy efficiency.

B. Energy Consumption Evaluation

Figure 2 shows the total amount of energy used during the trajectory. The optimized O-CTC configuration uses only 10.38 units of energy, which is a reduction of roughly 67.4% compared to the nominal CTC's total energy cost of about 31.86 units. The optimized gains successfully suppress transient torque bursts and minimize fluctuations in actuator energy output, as evidenced by the smoother slope of the O-CTC curve. This demonstrates that the suggested optimization



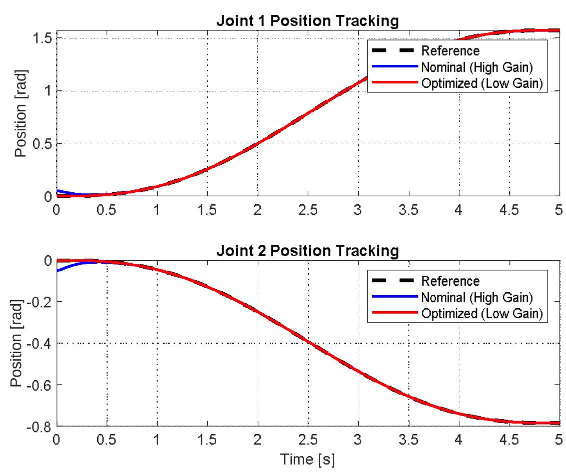


Figure 2 - Cumulative Energy Consumption Comparison   Figure 3 - Joint Position Tracking and Dynamic Behaviour

strategy is a workable way to save a substantial amount of energy without sacrificing control stability or accuracy.

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C. Tracking Accuracy and Dynamic Behavior

As illustrated in Figure 3, the joint trajectories acquired under the two control schemes are contrasted with the intended reference trajectory in order to evaluate motion precision. Throughout the 5-second motion sequence, both the nominal and optimized controllers exhibit high-fidelity tracking, keeping the maximum position error below 0.005 rad, meeting the design constraint. Although transient convergence is slightly slower due to the optimized gains, steady-state accuracy is essentially the same. This result emphasizes that systematic gain selection can improve energy efficiency without compromising dynamic accuracy or responsiveness.

D. RMS Torque Evaluation

The comparison of the Root Mean Square (RMS) torque values for the two joints under the two control configurations is shown in Figure 4. The average actuator load during the motion is quantitatively indicated by the RMS torque. According to the results, the optimized controller reduces RMS torque by over 60% when compared to the nominal case. For systems that need longer operating lifetimes or lightweight designs, this decrease means smoother torque delivery and less fatigue stress on actuators.

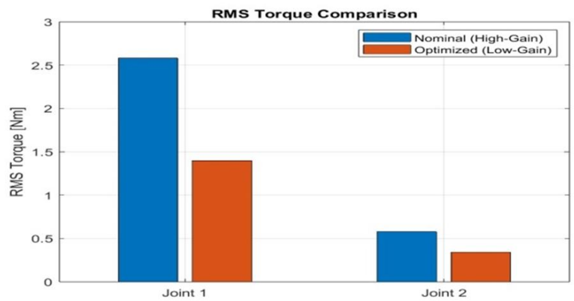

Figure 4 - RMS Torque Comparison Between Controllers

E. Instantaneous Power Analysis

Figure 5's instantaneous power profiles shed more light on how both control schemes behave in terms of energy over time. During the acceleration and deceleration phases, the nominal controller displays large transient spikes and high-frequency power oscillations, which are signs of inefficient torque activity. The optimized controller, on the other hand, results in a smoother power profile with less temporal variance and amplitude. By reducing energy waste from needless torque fluctuations, the optimized gains allow for more consistent actuator performance, as evidenced by this improved energy distribution.

The advantages of the suggested Optimized Computed Torque Controller (O-CTC) are further supported by quantitative results in addition to the qualitative observations. The optimized controller only needed 10.38 $Nm^2 \cdot s$, a reduction of about 67 percent in energy consumption compared to the nominal controller's total cumulative energy consumption of 31.86 $Nm^2 \cdot s$. The overall load on the actuators was lessened when the peak torque demand on Joint 1 decreased from roughly 10 Nm to 6 Nm and on Joint 2 from 2 Nm to 1.1 Nm. The optimized controller's maximum trajectory tracking error was 0.0047 rad, well within the predetermined 0.005 rad limit. These numbers unequivocally demonstrate that significant energy savings were attained without sacrificing motion control accuracy. These results are collectively depicted in Figures 1 through 5, which show the torque response, energy consumption, position tracking accuracy, instantaneous power comparison, and torque–error trade-off. When taken as a whole, they show that the optimized controller produces more consistent torque behavior, lower power consumption, and accurate tracking.

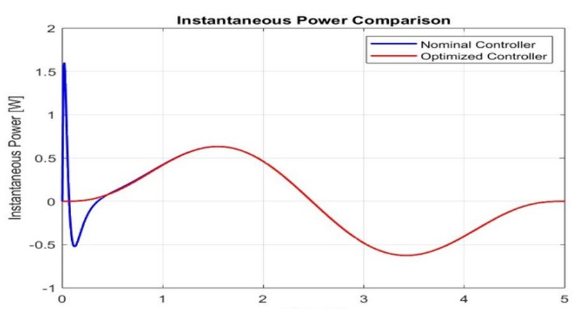

Figure 5 - Instantaneous Power Comparison

VIII. CONCLUSION

This work presented a comprehensive framework for achieving energy-efficient trajectory tracking in robotic manipulators by optimizing computed torque controller gains. Starting with a complete Euler–Lagrange dynamic model for a 2-DOF planar manipulator, the study established the foundation for accurate inverse dynamics control. The conventional computed torque control (CTC) scheme was extended to an optimization-based variant (O-CTC), formulated as a constrained nonlinear problem minimizing the integral of squared joint torque while maintaining strict tracking accuracy [10]. Simulation results showed that the optimized controller achieved a 67% reduction in total energy cost, significantly lower torque peaks, and tracking errors below 0.005 radians, confirming improved efficiency without loss of precision. These findings demonstrate that energy-aware gain tuning can effectively balance performance and sustainability in robotic control systems.

Beyond the numerical results, the study underscores the importance of optimization-driven control design. By incorporating energy considerations into the control synthesis stage, it offers a scalable and adaptable approach for developing efficient, low-wear robotic manipulators. Future work may explore real-time adaptive optimization, machine learning–based parameter tuning, and experimental validation on physical robotic platforms.

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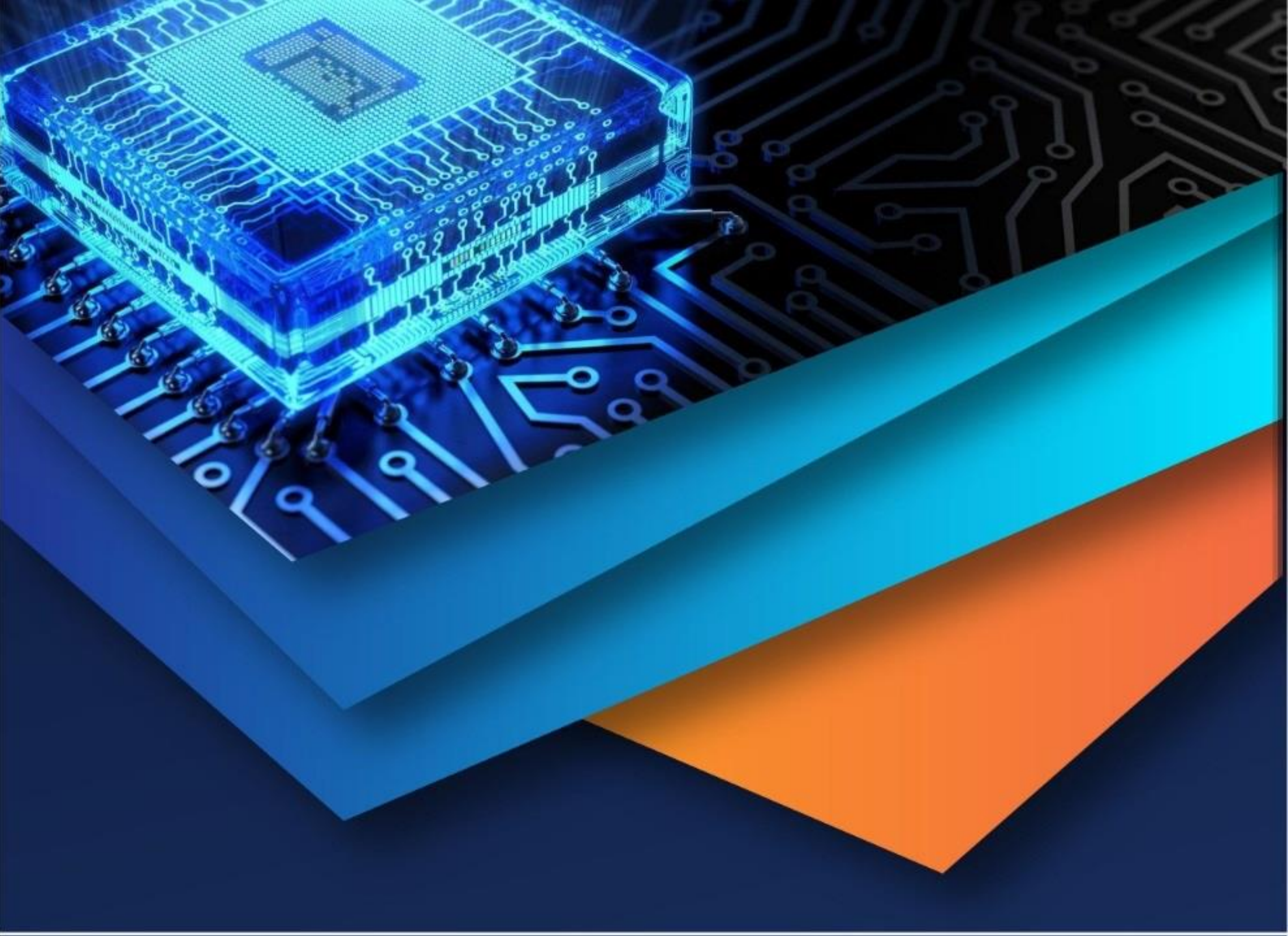

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