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Effective Control of a Robotic Manipulator's Trajectory Tracking through the utilization of an Optimal Linear Quadratic Gaussian (LQG) controller enhanced by the Improved Particle Swarm Optimization (IPSO) Algorithm

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Abstract:

This paper introduces a technique for modeling and effectively controlling the trajectory tracking of a robotic manipulator through an LQG controller optimized by the IPSO algorithm. Extensive simulations have been conducted within the MATLAB simulation environment. The LQG, which combines a Kalman Filter (KF) and a Linear Quadratic Regulator (LQR), is developed to follow the desired input for the robotic manipulator while minimizing the impact of process and measurement noise on its performance. The parameters of the LQG controller, which include the elements of the state and control weighting matrices for the LQR and KF, are optimally adjusted using the IPSO method. The validation of the proposed hybrid LQG-IPSO controller is conducted based on the control criteria parameters. The findings demonstrate that the proposed hybrid LQG-IPSO controller can achieve excellent movement performance. To fully leverage the capabilities of the IPSO algorithm, careful adjustment and determination of IPSO parameters such as inertia weight, iteration count, acceleration constants, and particle quantity are essential. Therefore, The initial focus of this study is to conduct a comparative analysis of various fitness functions; simulation results indicate that the proposed hybrid LQG-IPSO control method achieves commendable fitness outcomes with minimal steady-state error (ess). Following this, a comparison of the performances of a robotic manipulator using the hybrid LQG-IPSO controller, hybrid LQR-IPSO controller, LQG controller, and LQR controller is also presented. Based on the analysis, it can be concluded that superior performance parameters are attained with the hybrid LQG-IPSO controller when compared to its counterparts—the hybrid LQR-IPSO controller, LQG controller, and LQR controller—offering enhanced performance.

Keywords: Linear Quadratic Gaussian (LQG) controller, Linear Quadratic Regulator (LQR) controller, Improved Particle Swarm Optimization (IPSO) algorithm, Particle Swarm Optimization (PSO) algorithm and MATLAB etc.

1. Introduction

Robots are in widespread use in recent times, they are used in industrial applications with articulated geometric types because articulated robotic manipulators are most commonly used in factories worldwide [1]. Articulated manipulators are the most common industrial robotic structures providing more than 50% of annual installations around the world [2]. Robotic manipulators are also employed for jobs that are too dirty, hazardous, and highly repetitive or boring to be suitable for humans [3]. Linear Quadratic Gaussian (LQG)

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optimal control technique is one of the modern controls which is based on Kalman Filter (KF) in combination with a Linear Quadratic Regulator (LQR) controller. LQG controllers can be successfully applied to both Linear Time-Variant (LTV) systems and Linear Time-Invariant (LTI) systems [4]. Many researchers attempted to find a way to tune the LQG controller parameters. They presented either trial and error or complicated procedures to set the controller parameters [5]. Therefore, more powerful intelligent optimization methods have been presented by researchers to find best global solution for many control problems in different applications fields such as Genetic Algorithm (GA) [6-8], Bacteria Foraging Optimization Algorithm (BFOA) [8], Big Bang-Big Crunch (BBBC) algorithm [9], Particle Swarm Optimization (PSO) algorithm [6, 10], Particle Swarm Inspired Evolutionary Algorithm (PS-IEA) [11], Artificial Bee Colony (ABC) [12]. Basic PSO has been improved with the thought of governance in human society and tuned of parameters dynamically. In this improvement, PSO used two possible leaders who have been selected on the basis of the vote [13]. The ability of search is improved by varying inertia weight dynamically. The adaptive method of turning the inertial weight is projected [14,15]. The acceleration coefficient and inertial weights are the influential parameters to enhance the solution accuracy [16–18]. The ability of the algorithm has enhanced by combining other search techniques with PSO [19]. Combination of evolutionary operators with PSO enhances the population diversity to avoid from neighborhood minima [20, 21] such as selection crossover and mutation. Therefore, the subsequent section describes the use of two evolutionary operators in enhancing the performance of PSO. In this paper , a LQG controller is proposed to track a robotic manipulator system. This paper is structured as follows: The nonlinear mathematical modeling of the robotic manipulator is provided in Sec. II. Control strategy that incorporates: Optimal control strategy (LQR and LQG control methods) and hybrid optimal control strategy (hybrid LQG-IPSO and hybrid LQR-IPSO control methods) is introduced in Sec. III. Analysis of Simulation Results is considered in Sec. IV. Conclusion is presented in Sec. V.

2. Robotic Manipulator's Nonlinear Mathematical Modeling

Kinematics and dynamics of robot manipulators models Both are used widely in the simulation of motion, analysis of robot manipulator structures, and design of control algorithms [22].

2.1 Forward and Inverse Kinematic of Robotic Manipulators

Kinematics is the branch of mechanics that deals with the motion of the bodies and system without considering the force [23]. Robot kinematic studies the relationship between the linkages of robot with the position, orientation and acceleration as shown in figure 1

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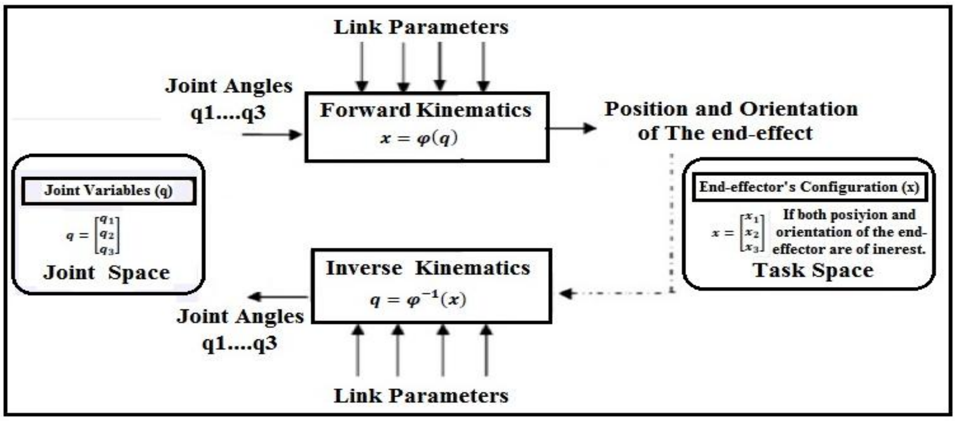

Figure 1: The connection between the robot's links and its acceleration, position, and orientation

2.2 The Dynamic Model of Robotic Manipulator

Figure 2 displays the robotic manipulator model. The dynamic equation, which is represented by ordinary differential equations, explains the relationship between force and motion. The actuators' applied forces and torques to the joints are indicated by (τ), which cause the joint angles to change. The joints' position, velocity, and acceleration are displayed by the vectors ($q, \dot{q}, \ddot{q}$).

$$\text{Forces: } \tau = \begin{bmatrix}\tau_1\\\tau_2\\\tau_3\end{bmatrix}, \text{Motion: } q = \begin{bmatrix}q_1\\q_2\\q_3\end{bmatrix}, \dot{q} = \begin{bmatrix}\dot{q}_1\\\dot{q}_2\\\dot{q}_3\end{bmatrix}, \ddot{q} = \begin{bmatrix}\ddot{q}_1\\\ddot{q}_2\\\ddot{q}_3\end{bmatrix}$$

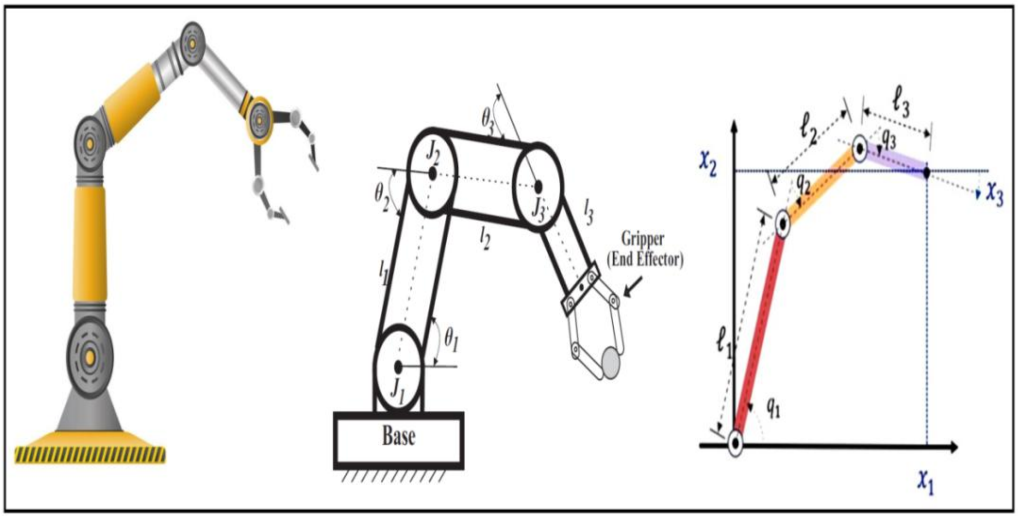

Figure 2: The robotic manipulator model.

There are different ways to calculate the dynamic model of a mechanical system, it's usually easer to use the Euler-Lagrange formulation to calculate the dynamic model and therefore this method will be chosen in this paper. The Nonlinear dynamics that describe the physics of the robotic manipulator is as follows

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right)-\frac{\partial L}{\partial q_i}=Q_i \tag{1}$$

Where

Q_i :→ is the generalized force

L :→ is the Lagrangian

To use Euler-Lagrange formulation, we first need to form the lagrangian of the system, the Lagrangian equation formalism (L) is defined as

$$L=KE-PE \tag{2}$$

Where

KE: → is kinetic energy $KE(q,\dot{q})$

PE: → is potential energy $PE(q)$

The kinetic energy (KE) of robotic manipulator is as follows

$$K(q,\dot{q})=\frac{1}{2}\dot{q}^T M(q)\dot{q} \tag{3}$$

Where

$M(q)$: → is the nxn inertia matrix which is symmetric and position define

Let's now substitute the lagrangian into Euler-Lagrange formulation and calculate the dynamical model of a robot manipulator

$$L(q,\dot{q})=KE(q,\dot{q})-PE(q)=\frac{1}{2}\dot{q}^T M(q)\dot{q}-PE(q) \tag{4}$$

The partial derivative of the lagrangian with respect to ($\dot{q}$) is

$$\frac{\partial L(q,\dot{q})}{\partial \dot{q}}= M(q)\dot{q} \tag{5}$$

Then, we take the derivative of equation (5)

$$\frac{d}{dt}\left(\frac{\partial L(q,\dot{q})}{\partial \dot{q}}\right)=\frac{d}{dt}\,(M(q)\dot{q})=\dot{M}(q)\dot{q}+M(q)\ddot{q} \tag{6}$$

Until now, we have calculate the first term on the left hand side of the lagrangian equation, to find the second term as should take the partial of the lagrangian with respect to (q) and can be written in this form as kinetic energy

$$\frac{\partial L(q,\dot{q})}{\partial \dot{q}}=\frac{\partial KE(q,\dot{q})}{\partial q}-\frac{\partial PE(q)}{\partial q}=\frac{1}{2}\frac{\partial}{\partial q}(\dot{q}^T M(q)\dot{q})-\frac{\partial PE(q)}{\partial q} \tag{7}$$

If we substitute these two terms into the lagrangian equation, we see the dynamical model of the robot manipulator as in this form

$$\frac{d}{dt}\left(\frac{\partial L(q,\dot{q})}{\partial \dot{q}}\right)-\frac{\partial L(q,\dot{q})}{\partial q}=\tau$$

$$M(q)\ddot{q}+\dot{M}(q)\dot{q}-\frac{1}{2}\frac{\partial}{\partial q}(\dot{q}^T M(q)\dot{q})+\frac{\partial p(q)}{\partial q}=\tau \tag{8}$$

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+g(q)=\tau \tag{9}$$

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Where

$q \in \mathbb{R}^n$: → is vector of joint coordinates

$M(q) \in \mathbb{R}^{nxn}$: → is inertia matrix

$C(q,\dot{q})\dot{q} = \dot{M}(q)\dot{q} - \frac{1}{2}\frac{\partial}{\partial q}(\dot{q}^T M(q)\dot{q}) \in \mathbb{R}^n$: →is the vector of coriolis and centrifugal forces

$g(q) = \frac{\partial p(q)}{\partial q}$: → is vector of gravitational forces (gravity forces)

$\tau \in \mathbb{R}^n$: → is vector of joint torques, τ represents the torque with which the system is pushed

Figures 3 and 4 illustrate the procedures for locating a robot manipulator's dynamic model and the block diagram of a robotic manipulator control system, respectively.

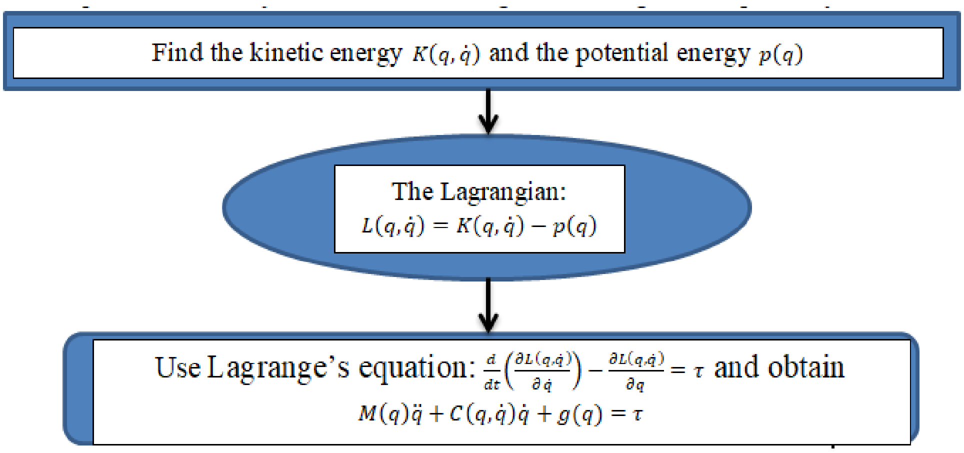

Figure 3: The steps to find the dynamic model of a robot manipulator

2.3 Control Problem

In this paper, we explain the control problem of robot manipulators and discuss the objectives the constraints and the control inputs and outputs robot manipulator,. Consider the dynamical model of an end degree of freedom robot manipulator

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau \qquad (10)$$

- **Regulation Problem (position control)**

The objective in the regulation or position control problem is to find the vector of joint torques (τ) such that the end effector converges to the desired position using the inverse kinematics

$$\lim_{t\to\infty} q(t) = q_d \qquad (11)$$

- **Tracking Problem (Motion Control)**

In the tracking or motion control problem the objective is to find the vector tau such that $q(t)$ of t follows the time varying trajectory $q_d(t)$

A. Position Error

It's convenient to define a joint position error vector or simply the position error as

$$\tilde{q}(t) = q_d(t) - q(t) \tag{12}$$

- The control objective in regulation (position control) problem is to find the vector (τ) such that

$$\lim_{t\to\infty} q(t) = q_d - q(t) = 0 \tag{13}$$

- The control objective in tracking (motion control) problem is to find the vector (τ) such that

$$\lim_{t\to\infty} \tilde{q}(t) = q_d(t) - q(t) = 0 \tag{14}$$

- The control objective is satisfied if $(\tilde{q} = 0,\ \dot{\tilde{q}} = 0,\ \ddot{\tilde{q}} = 0)$ is an asymptotically stable equilibrium
- In general, the control law is to be expressed as

$$\tau = \tau(q, \dot{q}, \ddot{q}, q_d, \dot{q}_d, \ddot{q}_d, M(q), C(q, \dot{q}), g(q)) \tag{15}$$

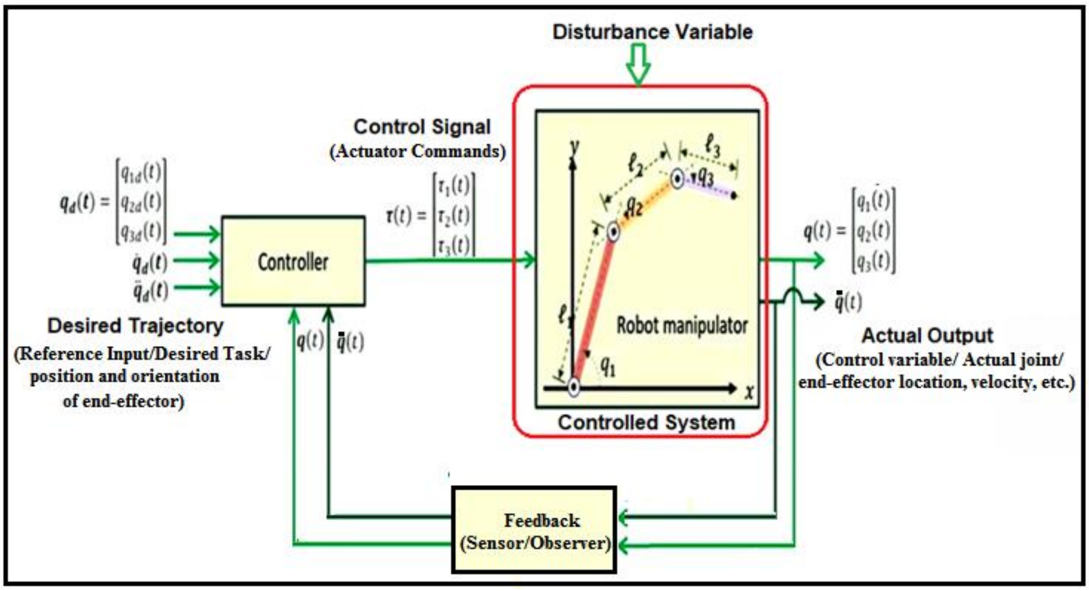

Figure 4: A robotic manipulator control system block diagram.

3. Optimal Control Strategy

3.1 Improved Particle Swarm Optimization (IPSO) Algorithm

The PSO algorithm was first introduced in 1995 by Kennedy and Eberhart, and was further expanded in 1997 [24]. Figure 5 displays the pseudo code for the suggested IPSO algorithm's implementation procedure.

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Pseudo Code of Improved Particle Swarm Optimization (IPSO)

1. Input
   - Objective function (fitness function), upper bound (ub) and lower bound (lb), population size or number of particles in the swarm (N), Inertia weight (ω_{max}, ω_{min}), number of decision variables (Var), individual and social cognitive or acceleration coefficients (c_1 and c_2), (r_1 and r_2) are two separately uniformly distributed random numbers in the range [0,1], maximum number of iteration (T_{max})
2. Initialization
   - Initialize random position (x) and velocity (v) within search space boundary
   - Assign P_{best} and G_{best} (Based on the objective function)
3. Loop
   - For $iter = 1{:}T_{max}$
   - For $i = 1{:}N$
   - For n=1:Var
   - Update Inertia Weight $\omega = \omega_{max} - \left(\frac{\omega_{max} - \omega_{min}}{T_{max}}\right) * iter$
   - Update velocity: $v(t) = \omega * v_i(t-1) + c_1 * r_1 * (Pbest_i - x_i(t-1)) + c_2 * r_2 * (Gbest - x_i(t-1))$
   - Update Position: $x_i(t) = x_i(t-1) + v_1(t)$
   - Check $x_i(t)$ within boundary: If $x_i(t) > x_{ub} \rightarrow x_i(t) = x_{ub}$ & $If\ x_i(t) < x_{lb} \rightarrow x_i(t) = x_{lb}$
   - Evaluate the objective function fx_i
   - Update P_{best} and G_{best} : $Pbest_i = x_i\ if\ fx_i\ better\ than\ f_{Pbest_i}$ & $Gbest = Pbest_i\ if\ f_{Pbest_i}\ better\ than\ f_{Gbest}$
   - If there is no convergence of the current solution & If $iter > T_{max}$ go to Loop
   Print $Gbest\ and\ f_{Gbest}$

Figure 5: Pseudo code of implementation process of proposed IPSO algorithm

3.2 Linear Quadratic Regulator (LQR) Control System

The optimal control problem is to find a control u which causes the system

$$\dot{X} = g(x(t), u(t), t) \quad (16)$$

To follow an optimal trajectory x(t) that minimizes the performance criterion, or cost function

$$J = \int_{t_0}^{t_1} h(x(t), u(t), t)dt \quad (17)$$

The problem is one of constrained functional minimization a quadratic performance index or quadratic cost function is

$$J = \int_0^{\infty} (x^T Q x + u^T R u)dt \quad (18)$$

Where

Q: →State weighting matrix (square, symmetric and non-negative definite)

R: →Control weighting matrix (square, symmetric and positive definite)

J: → Is a scalar quantity

The optimal control law or state feedback law is

$$U(t) = -Kx(t) \quad (19)$$

Where

K: → Is the controller gain or state feedback gain matrix and a value of K that will produce a desired set of closed-loop poles.

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The state feedback gain matrix (K) is found by [8]

$$K = R^{-1}B^{T}P \quad (20)$$

The matrix Riccati equation or algebraic Riccati equation is

$$Q + PA + A^{T}P - PBR^{-1}B^{T}P = 0 \quad (21)$$

The discrete quadratic performance index or discrete quadratic cost function is

$$J = \sum_{K=0}^{N-1}\left(x^{T}(k)Qx(k) + u^{T}(k)Ru(k)\right)T \quad (22)$$

The discrete solution of the state equation is

$$X(k+1) = A(T)x(k) + B(T)u(k) \quad (23)$$

The discrete solution of the matrix Riccati equation is [15]

$$K(N-(k+1)) = [TR + B^{T}(T)P(N-k)B(T)]^{-1}B^{T}(T)P(N-k)A(T) \quad (24)$$

And

$$P(N-(k+1)) = \left[TQ + K^{T}\left(N-(k+1)\right)TRK(N-(k+1))\right] + \left[A(T) - B(T)K\left(N-(k+1)\right)\right]^{T}P(N-k)\left[A(T) - B(T)K\left(N-(k+)\right)\right] \quad (25)$$

The optimal control law at step k is

$$U(k) = -K(k)x(k) \quad (26)$$

Figure 6 shows LQR control system

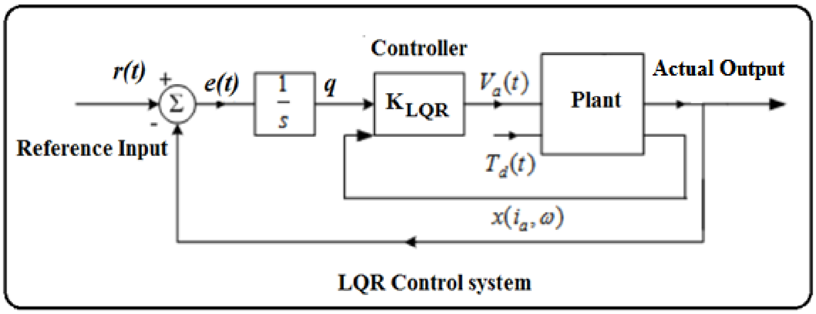

Figure 6: Control System for LQR

3.3 Kalman Filter State Estimator

Measurements z(k+1)T contain a Gaussian noise sequence v(k+1)T as shown in figure 7 [25].

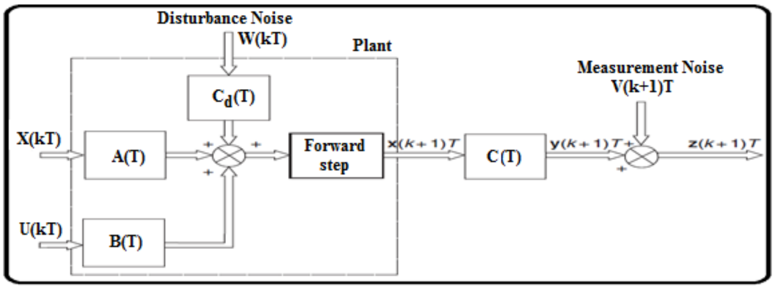

Figure 7: Plant with disturbance and measurements noise

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The state estimate $\hat{x}(k+1/k+1)$ is obtained calculating the predicted state $\hat{x}(k+1/k)$ from

$$\hat{x}(k+1/k)T = A(T)\hat{x}(k/k)T + B(T)U(T) \quad (27)$$

And the determine the estimated state at time (k+1)T using

$$\hat{x}(k+1/k+1)T = \hat{x}(k+1/k)T + K(k+1)[Z(k+1)T - C(T)\hat{x}(k+1/k)T] \quad (28)$$

The vector of measurements is given by

$$Z(k+1)T = C(T)xk+1)T + V(k+1)T \quad (29)$$

Where

$Z(k+1)T$: → is the measurement vector

$C(T)$: → is the measurement matrix

$V(k+1)T$: → is a Gaussian noise sequence

The kalman gain matrix [K] is obtained from

$$P(k+1/k) = A(T)P(k/k)A^T(T) + C_d(T)QC_d^T(T) \quad (30)$$

$$K(k+1) = P(k+1/k)C^T(T)[C(T)P(k+1/K)C^T(T) + R]^{-1} \quad (31)$$

$$P(k+1/k+1) = [I - K(k+1)C(T)]P(k+1/k) \quad (32)$$

Equations (27) to (32) are illustrated in figure 8 [25], which shows the block diagram of the Kalman filter is

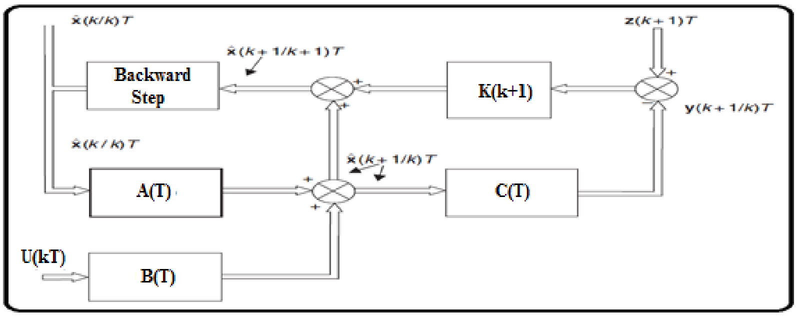


Figure 8: The Kalman Filter's block schematic.

3.4 System of Linear Quadratic Gaussian (LQG) Control

LQG is shown in figure 9.

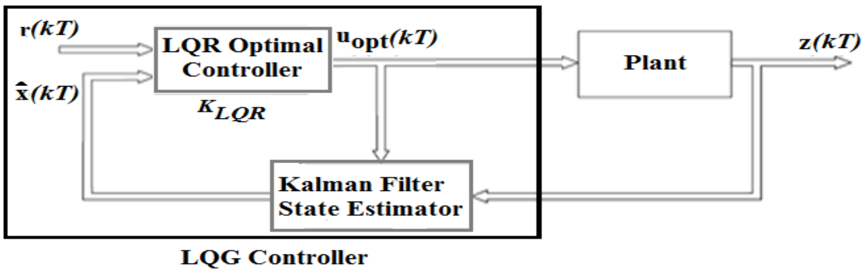


Figure 9: Scheme for the Linear Quadratic Gaussian (LQG) control system

Designing of optimal LQG controller with the feedback controller designed in such a way that it minimizes cost function [26].

$$J = \lim_{n\to\infty} E[\frac{1}{T}\int_0^T (x^T(t)Qx(t) + u^T(t)Ru(t))dt] \qquad (33)$$

The continuous time solution to the optimal observer problem is [28]

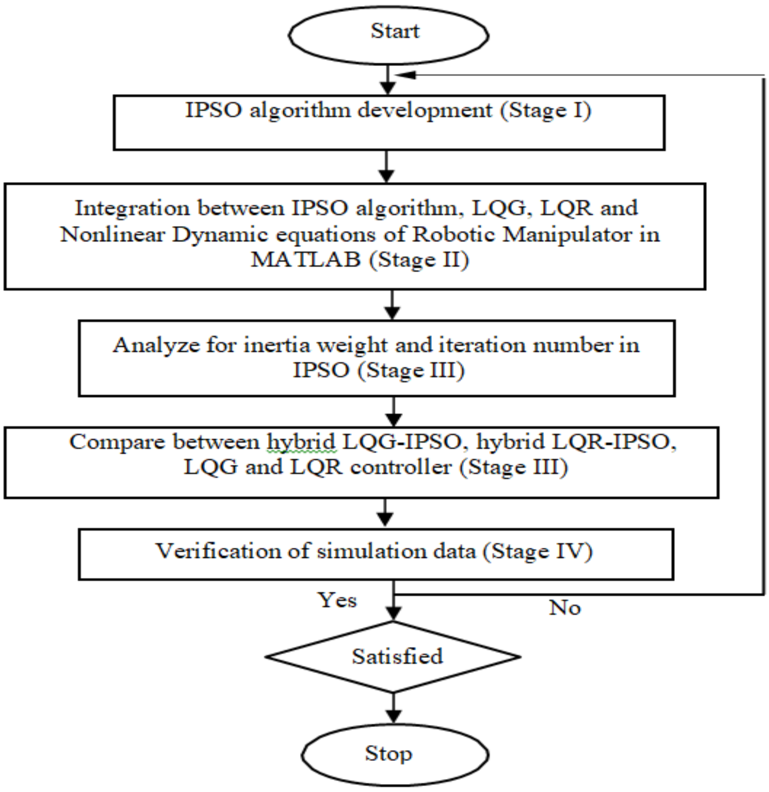
$$L = P_0 C^T R_0^{-1} \qquad (34)$$

Where P_0 is the solution of the algebraic Riccati equation:

$$AP_0 + P_0A^T - P_0C^TR_0^{-1}CP_0 + Q_0 = 0 \qquad (35)$$

3.5 Hybrid IPSO-LQG Controller

The primary purpose of the hybrid LQG-IPSO control method is to provide the controlled system (plant) with an excellent step response output. The flow diagram for the techniques used in this investigation is displayed in Figure 11.



Figutre 10: Research Method's Flow Diagram

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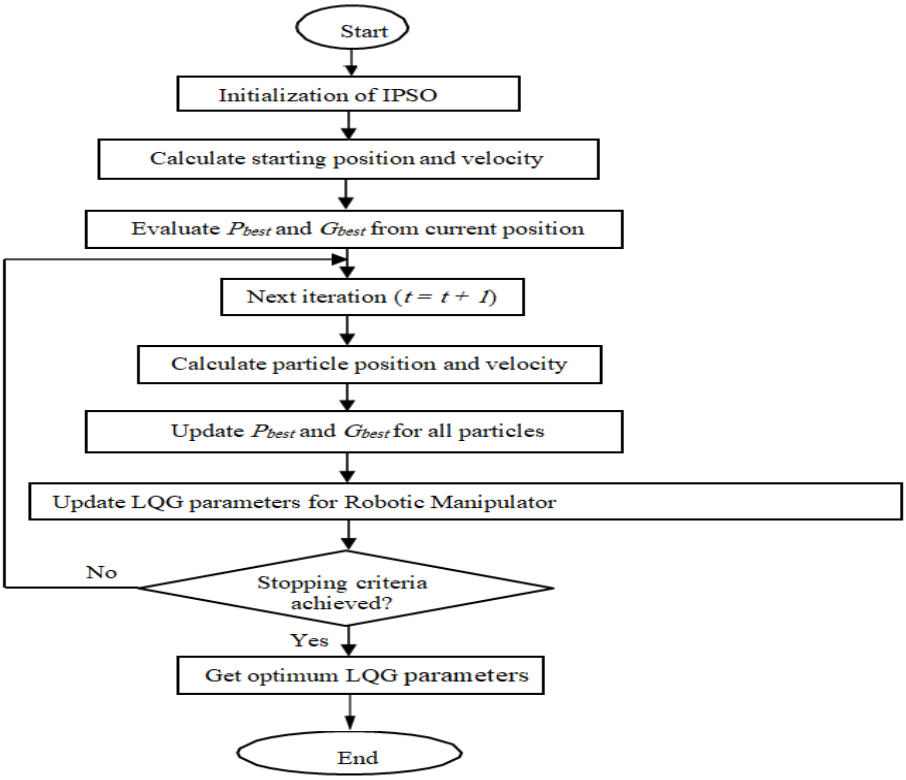

Figure 11: Process Flow of the hybrid LQG-IPSO controller.

Figure 11 shows the process flow for implementing the IPSO-based LQG and LQR controller, and Figure 12 shows how to design a hybrid LQG IPSO controller for a robotic manipulator.

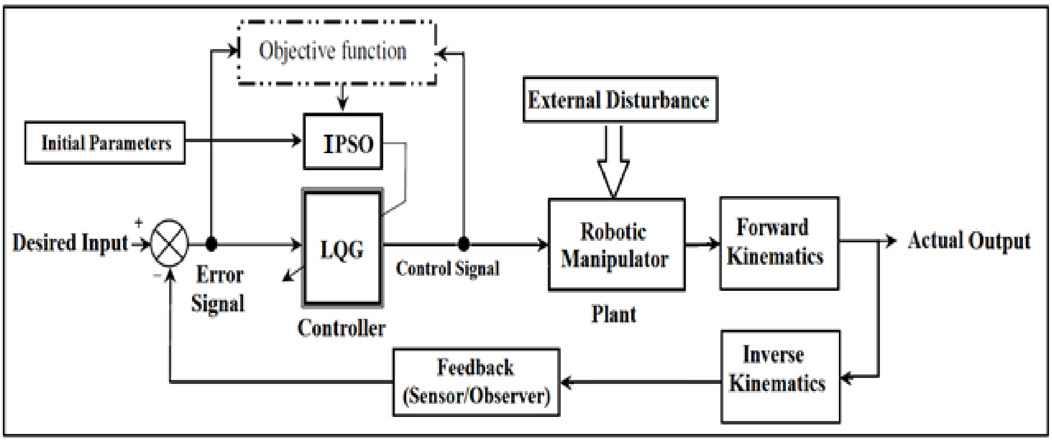

Figure 12: Design of the Hybrid LQG-IPSO controller.

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The following equations will be used to measure various fitness functions for this study.

- $IAE = \int_0^t |e(t)|dt$ (36)
- $ITAE = \int_0^t t|e(t)|dt$ (37)
- $ISE = \int_0^t (e(t))^2 dt$ (38)
- $ITSE = \int_0^t t(e(t))^2 dt$ (39)

4. Simulation Results and Discussion

4.1 Analysis Of Simulation Results Of Hybrid LQG-IPSO, Hybrid LQR-IPSO, LQR and LQG Controllers

The simulation results of the robotic manipulator with hybrid LQG-IPSO controller, hybrid LQR-IPSO controller, LQR controller and LQG controller under the effect of random loads are shown in figure 13, Figure 14, Table 1 and Table 2. On the other side, Table 2 comparison for all fitness functions or performance indices parameters (IAE, ITAE, ISE, ITSE) of a robotic manipulator under the effect of random loads with hybrid LQG-IPSO controller, hybrid LQR-IPSO controller, LQR controller and LQG controller and for further clarification.

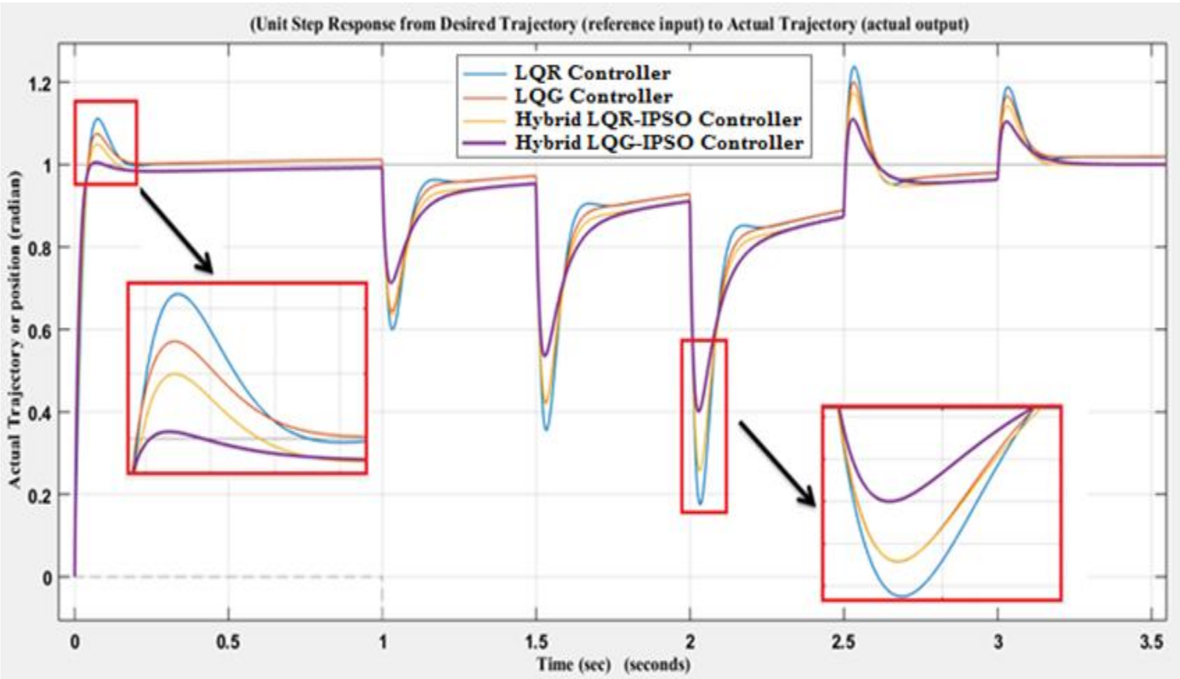

Figure 13: The Simulation results of the Robotic Manipulator with Hybrid LQG-IPSO, Hybrid LQR-IPSO, LQR and LQG Controller under the effect of Random Loads

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Table 1 Trajectory Tracking performance comparison of the Robotic Manipulator with optimal control and hybrid optimal control strategies

The Robotic Manipulator When Subjected to Arbitrary Loads				
Specifications for the Time Domain	Method of Control			
	Optimal Control Approach		Hybrid Optimal Control Approach	
	LQR Controller	LQG Controller	Hybrid LQR-IPSO Controller	Hybrid LQG-IPSO Controller
Maximum Overshoot (M_p)	11.114 %	7.4747 %	4.9728 %	0.54333%
error of steady state (e_{ss})	0.019969	0.019971	0.000027152	0.000024772
Damping ratio (ζ)	0.57309	0.63665	0.69076	0.85659

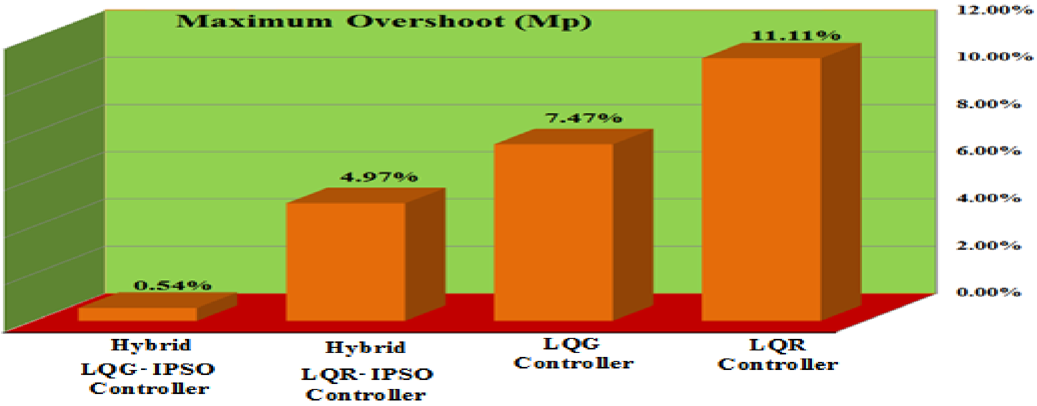

Figure 14: Maximum Overshoot (%Mp) Comparison for Hybrid LQG-IPSO Controller, Hybrid LQR-IPSO Controller, LQR Controller and LQG Controller.

Table 2 Comparison for all Fitness Functions (performance indices parameters) Hybrid LQG-IPSO Controller, Hybrid LQR-IPSO Controller, LQR Controller and LQG Controller.

Robotic Manipulator with the effect of Random Loads				
Control Method	Fitness Functions			
	$IAE = \int_0^t \lvert e(t)\rvert dt$	$ITAE = \int_0^t t\lvert e(t)\rvert dt$	$ISE = \int_0^t (e(t))^2 dt$	$ITSE = \int_0^t t(e(t))^2 dt$
LQR Control Method	0.0998445667	0.2496114166	0.0019937875	0.0049844687
LQG Control Method	0.0998535173	0.2496337932	0.0019941450	0.0049853625
Hybrid LQR-IPSO Control Method	0.0001357600	0.0003394001	0.0000000037	0.0000000092
Hybrid LQG-IPSO Control Method	0.0001238615	0.0003096539	0.0000000031	0.0000000077

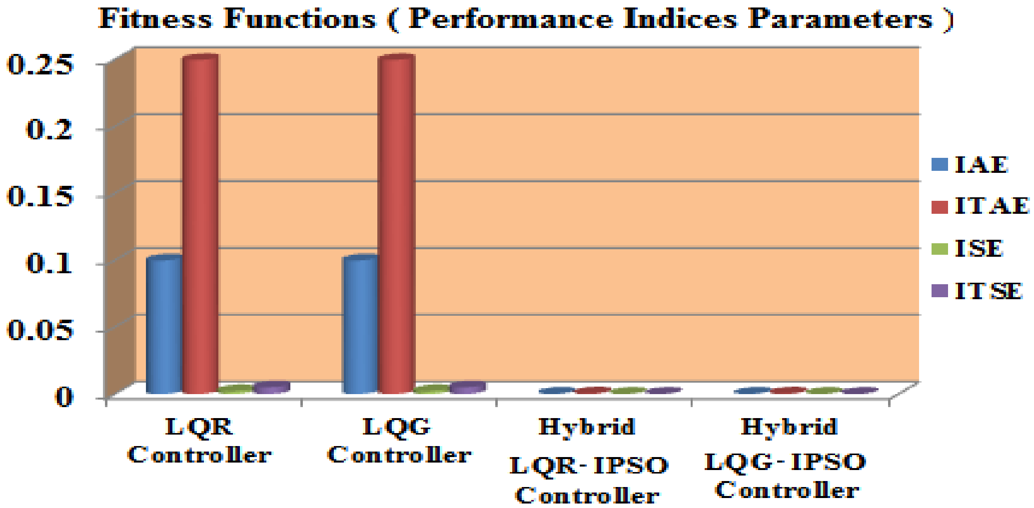

Figure 15: Comparison of different fitness functions or performance indices parameters (*IAE, ITAE, ISE, ITSE*) for Hybrid LQG-IPSO, Hybrid LQR-IPSO, LQR and LQG Controller

The simulation indicates that, in comparison to hybrid LQR-IPSO, LQR, and LQG controllers, the hybrid LQG-IPSO controller is the best controller.

5. Conclusion

The hybrid LQG-IPSO control method has been shown in this paper to improve the tracking, stability, and accuracy of the robotic manipulator under the influence of noise suppression, disturbance attenuation, and different random loads to achieve good tracking, where a simulation has been done to verify the proposed control scheme and to compare it with other control schemes, extensive simulations have been done to present comparative analysis between different fitness functions (IAE, ITAE, ISE, ITSE), Simulation results show that hybrid LQG-IPSO controller provide a good fitness achievement with low steady state error (e_{ss}). The hybrid LQG-IPSO control method outperforms other control methods, as demonstrated by the simulation results. Additionally, all of the system's design specifications have been confirmed. Thus, the optimal control strategy is the hybrid LQG-IPSO control strategy. Given the nonlinearities and uncertainties of the robotic manipulator, this control approach appears to hold great promise for improving control performance and increasing flexibility in real-world applications.

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