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# LQR Based Cooperative Vibration Suppression in Dual Flexible Robotic Manipulators with Unequal Load Sharing

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***Abstract: This paper examines cooperative vibration suppression in two flexible robotic manipulators lifting a common load under unequal load sharing scenarios. Flexible motions and imbalanced force distribution tend to unwanted oscillations, compromising manipulation precision and payload stability. To overcome this challenge, a simulation environment is established in MATLAB, simulating two UR5 robotic manipulators lifting a common load. Time and frequency domain vibration responses of the payload are examined, and a control technique, Linear Quadratic Regulator (LQR) to reduce the vibrations. It shows reduced payload oscillations and enhancement in the load sharing index, identifying the capability of the proposed method. Unlike existing studies that treat load imbalance as a disturbance, this work explicitly models unequal load sharing and demonstrates how cooperative control redistributes damping responsibility to suppress vibrations effectively.***
***Keywords: Vibration Suppression, Linear Quadratic Regulator (LQR), Dual Robotic Manipulator, Unequal Load Sharing, MATLAB Simulation.***

## I. INTRODUCTION

In recent years, robotic manipulators have increasingly found their way into precision manufacturing, aerospace assembly, and collaborative industrial processes over the past few years. Their implementation of cooperative manipulators has facilitated intricate operations like lifting and moving heavy or fragile payloads. However, when flexible manipulators share a payload, link flexibility, unsymmetrical force transmission, and dynamic robot-payload interaction can lead to oscillations and vibrations. Not only do these vibrations reduce positional accuracy but also increase the risk of payload instability as well as structural stress on the manipulator structures. Cooperative control of two robotic manipulators becomes challenging when the load is unevenly distributed, something that may happen due to uneven grasp points of end effectors, actuator characteristics or intentional task distribution. Classical rigid-body approximations are unable to counteract the effect of flexibility, and hence proper modelling and vibration suppression is needed to ensure reliable performance. Against such issues, advanced control methods, such as Linear Quadratic Regulator (LQR), are employed to minimize payload oscillations while maintaining the intended trajectory tracking. Simulation tests in virtual simulation environments like MATLAB allow detailed analysis of flexible link dynamics and uneven load sharing effects, therefore allowing proper design of optimal cooperative manipulation control strategy. This work considers cooperative vibration suppression in dual flexible manipulators handling a common payload under unequal load-sharing scenarios. The research provides insights in modelling flexible joints, with unequal load allocations, and LQR control used in enhancing stability and accuracy, to contribute to innovation in collaborative robotic systems.

Current research on cooperative robotic manipulation has started giving greater importance to safety, accuracy, and flexibility, especially with respect to human–robot cooperation, aerospace assembling, and automated logistics. Most current methods of cooperation, however, work on the assumption that either rigid robots or perfectly symmetric load sharing between robotic arms exist. Realistic environments, on the other hand, always pose some inequality due to grasping position offsets, actuator saturation, geometric asymmetry, and task-dependent force sharing. All these conditions impact vibration properties and, more importantly, control accuracy.

Vibration control in robotic manipulators has been highlighted in recent research, primarily for flexible links and cooperative dual-arm robots. Kalathinathan et al. [1] provided a comprehensive review of vibration reduction methods, including classical controllers such as PID and latest techniques such as Linear Quadratic Regulator (LQR) and input shaping for single-link and multi-link manipulators. These methods have been experimentally proven to enhance trajectory tracking and dampen oscillations significantly. Cooperative control in dual-arm manipulators has been researched to manage common loads, which generally respond with flexibility-induced vibrations.

Yukawa [2] researched cooperative control of two arms for a flexible vibrating object and concluded that cooperative motion is necessary to ensure non-amplification of oscillations. Jiang et al. [3] also compares PID, LQR, and sliding mode control for flexible joint robots and concludes that LQR provides improved vibration suppression and more precise trajectory tracking. Lima et al. [4] investigated position and vibration control of flexible link manipulators, showing that multiple control techniques can improve the overall system's stability. Innovative and adaptive control techniques have also been used. Ahmad and Zribi [5] developed predictive adaptive control for cooperative motion of multiple robots, with diminishing amplitudes of vibration and enhanced stability under conditions of uncertain loads.

Basic vibration theories of flexible systems have been presented by Thomson [6], laying the foundation for contemporary control implementations in manipulators. Current studies have included intelligent and hybrid control approaches. More recent works have also further expanded cooperative manipulation and vibration control with advanced models and control methods. Adaptive and robust cooperative controls were also introduced for dealing with uncertainties and dynamic changes of the parameters and payloads, and these were proven to provide more stability and vibration reduction for two-arm robots. Optimal and nonlinear control techniques were also employed for cooperative robotic systems, primarily for improving dynamic characteristics with external disturbance and structural flexibility. Though, most of these existing techniques usually depend either on full-order models or on load unbalance as external disturbances and, more importantly, as a dynamic system property of the cooperative system. Faris [7] merged fuzzy logic and LQR for vibration cancellation in two-link flexible manipulators and exhibited quicker convergence and insensitivity to parameter changes. Sanz [8] utilized optimal input shaping coupled with LQR to actively dampen oscillatory modes efficiently. Cooperative dual-manipulator control has been investigated further by AlYahmali and Hsia , Yagiz et al. [9], and Dellinger and Anderson [10], who studied the dynamics and the interplay of forces among various robots carrying flexible loads. Azadi et al. [11] presented robust control methods for two 5-DOF cooperating manipulators, ensuring stability under uncertainties in load and manipulator dynamics.

This indicates that to efficiently minimize vibrations in double flexible manipulators, it requires precise flexible link modelling, an appropriate cooperative control strategy, and sophisticated controllers such as LQR, input shaping, fuzzy logic, or sliding mode control. Although much progress has been achieved for single manipulators, dual-arm cooperative manipulation under unequal load sharing is an open area needing further research.

This research formulates a dynamic model for an unequal payload sharing dual flexible robotic manipulator and analyses the effects of structural flexibility on coordinated motion. Based on the above discussion, it can be clearly noted that although cooperative vibration reduction models have been extensively investigated in the field of vibration research, a detailed analysis of non-uniform load sharing in cooperative vibration models of a lower order remains uncharted territory. The major portion of existing models either considers single manipulators, considers symmetric force sharing, or resorts to higher-order models that make controller design a difficult task. A cooperative LQR-based control methodology is then applied to eliminate vibrations and ensure synchronized end-effector movement. A controller is setup to perform optimally, and a simulation setup is used to compare open-loop versus controlled responses. The findings explicitly show substantial vibration reduction and enhanced cooperative stability upon handling payloads.

The proposed method signifies the first attempt at developing a precise reduced-order model of cooperative vibration, encompassing the notion of unequal load sharing by using the allocation of asymmetric stiffness and damping coefficients. The proposed method encompasses the systematic mapping process of reduced-order vibration states into joint space torque control for dual-UR5 manipulators. Quantitative validation of the proposed method entails the comparison of LQR control with open loop control and PID control based on different scenarios of unequal loading. This focuses on the efficiency of the proposed method in enhancing system damping coefficients and reducing the natural frequency of the system. The proposed method encompasses the validation of the frequency domain FTP analysis through the evaluation of the Fast Fourier Transform validation domain for the frequency domain analysis of the system's primary vibrational modes and the suppression of the natural frequency of the system. The remainder of the paper is organized as follows: Section II presents the system modeling and reduced-order formulation, Section III describes the controller design and implementation, Section IV discusses simulation results and comparative analysis, and Section V concludes the paper with future research directions.

## II. METHODOLOGY

Here, the primary aim in this study is to maintain and minimize vibration in a dual robotic manipulator system that cooperatively lifts a common payload. A dual-manipulator system is made up of two robotic arms that collaborate to transport and move a single load.

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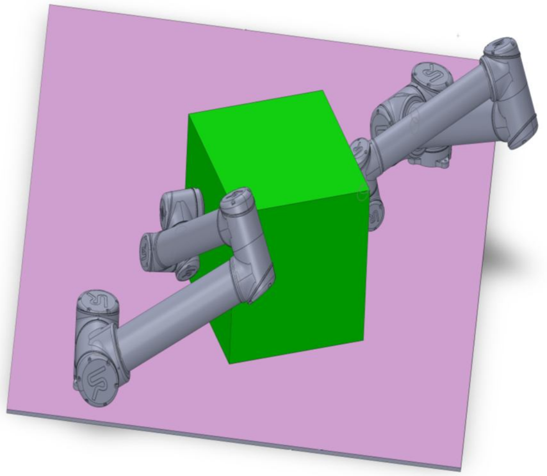
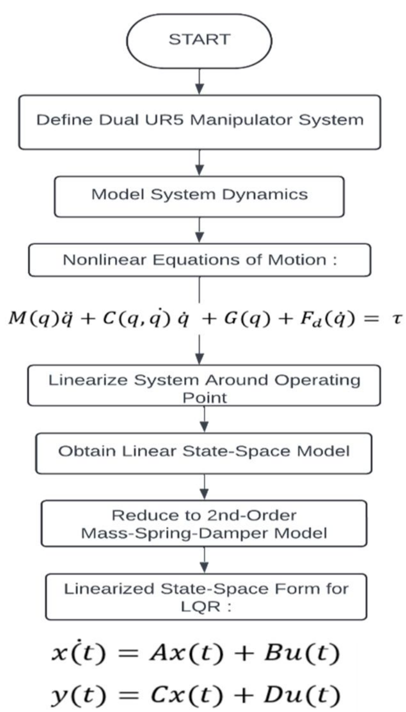


Fig.1(a) Dual UR5 Manipulators Sharing Common Payload

Fig.1(a) shows that two UR5 robotic manipulators are utilized here to lift one common payload. Here, manipulator carries part of the total load, but because of minute variations in arm stiffness, position, or torque capacity, there tends to be unequal load sharing. The resulting imbalance leads to unwanted vibrations and oscillations in the payload and the robot arms, lowering the stability, accuracy, and overall performance of system.

A full-order flexible-link or finite-element model of the dual-manipulator setup leads to a high-order nonlinear dynamic formulation. This significantly enhances computational complexity and is not well-suited for an optimal controller synthesis. Since the primary objective of this study is payload-level vibration suppression during cooperative manipulation, a reduced-order modelling approach is adopted. The dominant low-frequency payload vibration mode due to robot-payload interaction is approximated by a second order mass-spring-damper system. This model is valid in the low-frequency range of about 0-5 Hz, where most of the vibration energy is present during cooperative lifting. Higher-order flexible link bending modes, joint elasticity, and structural vibrations occur at higher frequencies and are, hence, not explicitly modelled. These effects lie outside the control bandwidth of the proposed LQR controller and are considered as unmodeled dynamics.



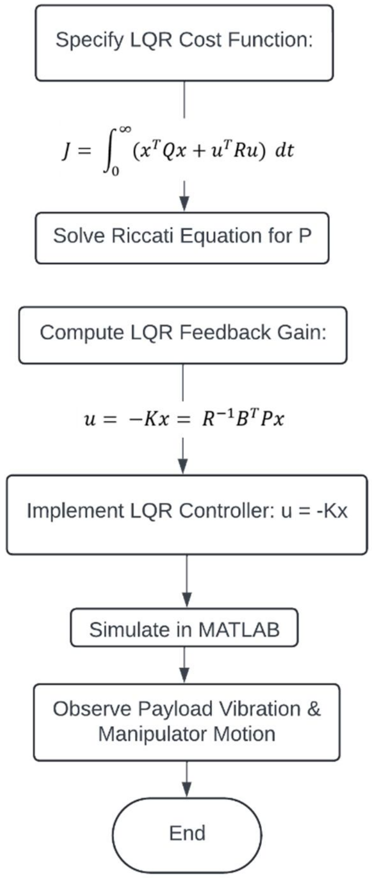



Fig.1(b) Logic Flow for Suppressing Vibration in Dual Flexible Manipulator

To address such challenges, an LQR controller is developed and integrated. The LQR controller is selected as it offers maximum control performance in terms of vibration amplitude minimization as well as control effort. In contrast to basic PID controllers, which concentrate on error correction alone, the LQR considers all system dynamics through the state-space description. This makes it suitable for vibration reduction in flexible robot systems. The controller seeks to attain smooth, efficient, and stable cooperative motion of the two UR5 manipulators, even with unequal loads.

The robotic system modelling starts with the equation of motion, which explains how the torques and forces influence the manipulator joints. The equation is presented as

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

Where $q$ is the vector of joint angles, $M$ is the mass matrix, $C$ includes Coriolis and centrifugal effects, $G$ is the gravity vector, $F_d$ accounts for damping, and $\tau$ represents joint torques applied by the actuators.

To apply linear control techniques, the non - linear system is linearized around an operating point that is the configuration in which both manipulators support the payload steadily. This linearization performs the Jacobian matrices that describe how small variations in joint positions and torques influence system behaviour in the neighbourhood of this operating point. Linearization provides a linear and time-invariant model, which is required for LQR controller synthesis.

To further reduce controller design, the joint–payload dynamics are modelled as a 2nd-order mass-spring-damper system, which captures the flexible dynamics of the dual manipulators effectively without being computationally complex. This is an efficient method for vibration analysis and control in MATLAB without building a complete complex dynamic model.

The reduced model is given as:

$$m\ddot{x} + (C_L + C_R)\dot{x} + (K_L + K_R)x = U_L + U_R$$

Where $C_L \neq C_R$
$K_L \neq K_R$

It is transformed to:

$$\dot{x}_1 = x_2$$

Now it conforms to the linear state-space form:

$$\dot{x}_2 = -\frac{k}{m}x_1 - \frac{c}{m}x^2 + \frac{1}{m}u$$

This is the linearized form used to design LQR.

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{c}{m} \end{bmatrix} x + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} u$$

$$y = [1\ \ 0]x$$

Employing this approach provides an efficient design and simulation of the LQR controller for vibration reduction in MATLAB without requiring a full complex robotic dynamics model. The simplification appropriately maintains the essential vibration characteristics without rendering the model too complicated.

The dynamic response of the reduced-order system can be written in state-space form as:

$$x\dot{(t)} = Ax(t) + Bu(t)$$

$$y(t) = Cx(t) + Du(t)$$

where $x(t)$ is the state vector (joint displacement and velocity), $u(t)$ is the control input (joint torque), and $y(t)$ is the output of the system (payload or joint displacement response).

The matrices of the system are:

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{c}{m} \end{bmatrix},\ B = \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix},\ C = [1\ \ 0],\ D = [0]$$

Here, m = 5kg is the mass of the payload, k = 800N/m is the approximate stiffness of the manipulator–payload link, and c = 10 Ns/m is the damping coefficient. Using these values yields:

$$A = \begin{bmatrix} 0 & 1 \\ -160 & -2 \end{bmatrix},\ B = \begin{bmatrix} 0 \\ 0.2 \end{bmatrix},\ C = [1\ \ 0],\ D = [0]$$

The LQR controller is specified to minimize the quadratic cost function:

$$J = \int_0^\infty (x^T Qx + u^T Ru)\ dt$$

where Q penalizes state variable deviations (vibrations and displacement), and R penalizes large control effort. Standard values employed in this work are:

$$Q = \begin{bmatrix} 100 & 0 \\ 0 & 1 \end{bmatrix},\ R = 0.01$$

These values provide importance to vibration suppression and stable torque control. The best feedback gain matrix K is determined by solving the Riccati equation:

$$A^T P + AP - PBR^{-1}B^T P + Q = 0$$

Once the Riccati equation has been solved for P, the feedback control law is:

$$u = -Kx = R^{-1}B^T Px$$

The continuous-time algebraic Riccati equation (CARE) is solved using MATLAB's lqr() function. The LQR controller produces torque from displacement and velocity feedback. It constantly corrects the actuator torques to minimize oscillations due to unsymmetrical load sharing.

To estimate the extent of uneven load distribution between the two manipulators, Load Sharing Index (LSI) is calculated as,

$$\text{LSI} = \frac{F_L}{F_L + F_R}$$

Where $F_L$, $F_R$ represent the interaction forces between the left and right manipulators and the payload respectively. An LSI value of 0.5 indicates equal sharing of the load, and any other value shows imbalance in the distribution of the forces. Even though the LQR control is not directly designed for LSI regulation, it indirectly affects LSI through cooperative torque distribution. The LQR optimum control action is weighted and delivered to the individual manipulating arms according to their equivalent stiffness and damping properties and, yields differentiated torque commands, affecting the resulting forces , to dynamically adjust the LSI and improve cooperative stability and suppression of vibrations in situations of unequal load sharing.

The reduced-order state-space model represents the dominant cooperative vibration dynamics of the payload and is used to design the LQR controller. The LQR state vector is defined as

$$x = [\ x_p \ \ \dot{x_p}\ ]^T$$

where $x_p$ , $\dot{x_p}$ denote the payload displacement and velocity along the lifting direction. The states are estimated from the end-effector Cartesian motion of the dual manipulators during the cooperative manipulation. The LQR control law generates an optimal scalar control force $u$, acting on the payload. This control input is mapped to joint-space torque commands of the two UR5 manipulators using a Jacobian transpose-based force–torque relationship,

$$\tau_i \ = \alpha_i J_i^T u, \ \ i \ \in \{L, R\}$$

where $J_i$ is the Jacobian matrix of the $i^{th}$ manipulator and is a load-sharing coefficient that distributes the control effort between the left and right arms. The torque allocation considered here allows this co-operative vibration suppression by using unequal load sharing between the manipulators.

Through real-time control of the torque, the controller minimizes payload vibration and maintains stable and synchronized movement of both UR5 manipulators during MATLAB simulation.

## III. IMPLEMENTATION

Simulation of the proposed cooperative dual-manipulator system was developed and implemented in MATLAB with two UR5 robots and a common payload. Every UR5 robot has six revolute joints, and the simulation used their dynamic and kinematic parameters to properly characterize motion and joint settings. The two robots were mounted on bases that were 0.8 meters apart from each other and aligned facing one another in a symmetrical configuration for cooperative payload handling. The payload was specified with size 0.3 m × 0.2 m × 0.15 m and a weight of 5 kg. It was simultaneously held by both UR5 manipulators, each from one side, through end-effector grasp offsets equal to half the payload width. The payload coordinates employed during the simulation were:

Initial Position (X, Y, Z): [0, 0.3, 0.3] m

Final Position (X, Y, Z): [0, 0.0, 0.5] m

These coordinates indicate the lifting and transportation movement of the payload from a lower and forward to a higher central position between the manipulators. The simulation was separated into four successive motion phases: The cooperative manipulation process consists of four primary motion phases. During the pre-grasp approach phase, both UR5 robotic arms transition from their home configurations to the pre-grasp poses close to the payload. During the grasping, lifting, and transportation phase, both manipulators concurrently grasp the payload and transport it along a smooth predetermined trajectory between the initial and final coordinates. In the payload release and pre-release phase, the payload is deliberately placed at the target final position, and then the two manipulators transition to a safe pre-release position so that they can detach smoothly. Lastly, in the return-to-home position stage, the two manipulators transition to their initial starting configurations, finishing the cooperative manipulation process.

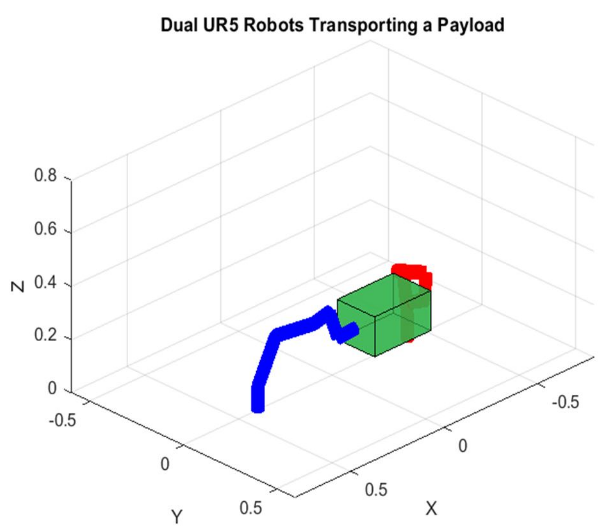



Fig.2(a) Dual UR5 Robots and Payload at Initial Position.

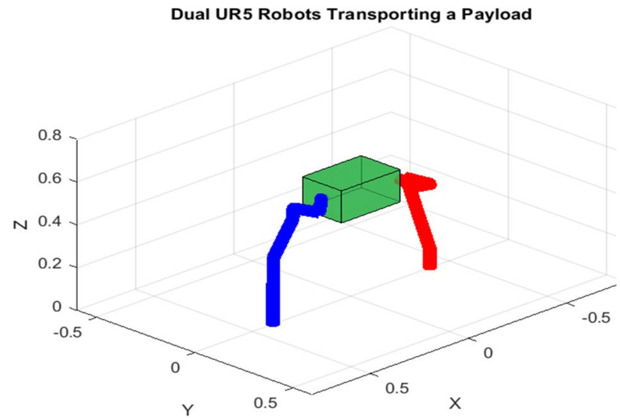



Fig.2(b) Dual UR5 Robots and Payload at Final Position.

Throughout the simulation, the two UR5 manipulators cooperatively grasp and move the payload from the start to the goal position. The initial and final configuration of the manipulators and the payload are illustrated in Fig.2(a) and Fig.2(b), respectively. In above Fig.2(a), At the initial position , both manipulators are set symmetrically on both sides of the payload at the coordinates [0, 0.3, 0.3] m, ready to lift the object. The left manipulator (red) and right manipulator (blue) stay aligned, which ensures secure grasping before the lifting process starts. In Fig.2(b), At the final position, the payload has been moved smoothly to the new destination at [0, 0.0, 0.5] m. The two manipulators modify their joint configurations collaboratively to keep the payload's orientation and stability during motion. The smooth and synchronized motion between the two arms validate the correctness of the inverse kinematics calculation and the coordinated control strategy performed in MATLAB.

Each step was performed through trajectory interpolation functions (trinterp) and inverse kinematics calculations (ikineUR5) to achieve smooth, collision-free motion. The joint coordinates were calculated iteratively with joint limit constraints and cooperative alignment of the arms. The LQR controller that was derived in the methodology section was realized using lqr() function. The controller calculated the optimal feedback gain matrix $K$ and then applied the control law $u = -Kx$ at each step of time. Feedback torque that was produced was utilized to stabilize both manipulators and reduce vibrations during cooperative lifting. Simulation environment had 3D visualization of both UR5 robots and the payload. Real-time visualization of the arm motion and payload trajectory was achieved using MATLAB plotting routines. At runtime, joint angles, rates, and torque responses were monitored to assess system stability and vibration characteristics. The LQR controller also dynamically compensated for any vibration caused by the non-uniform division of the load among the two manipulators. Thus, the payload exhibits smoother motion, reduced vibration, and improved positional accuracy. In conclusion, MATLAB-based simulation proves the proposed LQR vibration control technique for the dual UR5 manipulator system to ensure synchronized, stable, and vibration-free cooperative operation.

## IV. RESULTS AND DISCUSSIONS

The simulation results confirm the performance of the developed Linear Quadratic Regulator (LQR) cooperative control strategy in eliminating payload vibration for dual flexible robotic manipulators, with particular focus on the challenging situation of unequal load sharing. A primary observation is the significant decrease in payload vibrations and vibration energy when the LQR controller is activated, confirming it is effective in ensuring stability and precision in cooperative handling manipulators.

Table.1. Comparative Performance Metrics of Without Controller and LQR Controller Scenarios

| Scenario | Peak Displaceme nt (m) | Vibration Energy | MeanLeft Share |
|---|---|---|---|
| without_controller | 0.7007 | 21.6123 | 0.499 |
| lqr_controller | 0.5167 | 3.6680 | 0.498 |

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Table.1 validates the system performance with LQR controller against the open – loop system. Notable findings show that LQR system reduced the maximum payload vibration considerably, from peak displacement of 0.7007 m to 0.5167 m. Notably, controller recorded a resounding 83% reduction in residual oscillation, from vibration energy 21.6123 to merely 3.6680. This indicated the LQR's good ability to damp vibration but efficiently provide a general balance of equal load distribution, as testified by the near-equal mean left share values. The mean left share values, roughly 0.499 and 0.498 for the two scenarios, indicate that the load distribution between the left and right arms remains balanced even with the addition of the controller. This means that the LQR suppresses vibrations, and it does not compromise on the capacity to share loads or introduce asymmetry in the system dynamics. Overall, Overall, the outcomes confirm that the LQR controller maximizes vibration energy and amplitude but also provides load balance, proving its reliability for use in precise motion control and balanced operation with changing payloads.

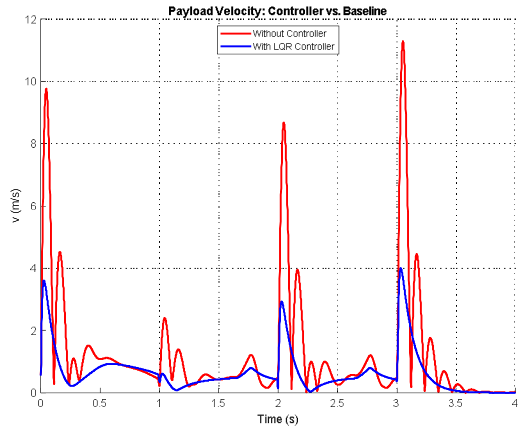


Fig.3(a) Payload Velocity: Comparison of System With LQR Controller and Without Controller

The Fig.3(a) plot evidently shows the significant enhancement in vibration performance offered by LQR controller. Without the controller, the system is highly unstable, and the payload velocity goes up to 11 m/s, especially at motion initiation and termination, showing maximum uncontrolled payload oscillation. On the other hand, LQR controller system is much more stable, with velocity spikes suppressed to less than 5 m/s. This indicates that the LQR controller efficiently dampens the payload motion and reduces vibration energy, leading to smooth operation with stability.

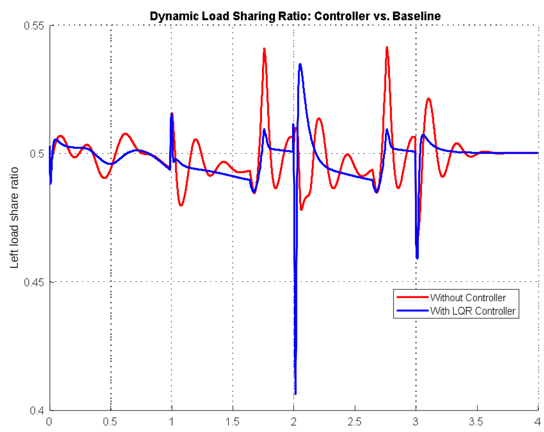


Fig.3(b) Dynamic Load Sharing Ratio: Comparison of System with LQR Controller and Without Controller

The above Fig.3(b) illustrates how the forces are regulated between the left Arm and right Arm. In open-loop system, the load remains close to an equal 0.5 portion but oscillates because of uncontrolled vibration. On the other hand, the LQR-controlled system demonstrates controlled and stable deviations in motion to adjust for balance as well as to minimize oscillation. Sudden dips at 2.0s indicate the LQR controller temporarily reallocated the force to the left arm, which having greater active damping gain 300 Ns/m compared to right actively dampen the residual vibration indicated in payload velocity plot.

This demonstrates the controller's capability for both damping and dynamically coordinating force cooperation arm having active damping gain of 100 Ns/m, to dampen the residual vibration indicated in the payload velocity plot. This demonstrates the controller's capability for both damping and coordinating force cooperation.

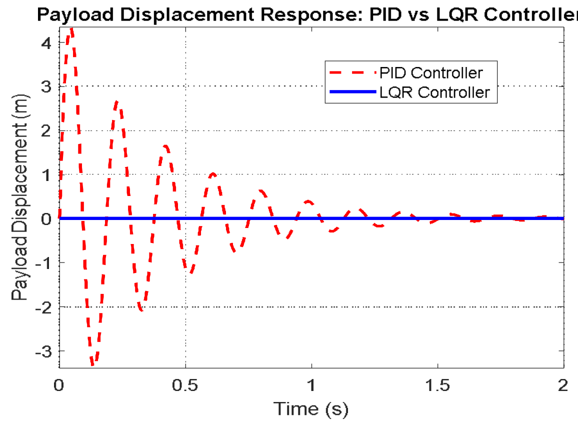


Fig.3(c) Payload Displacement: Comparison of System with PID and LQR Controller

To compare the effectiveness of the proposed LQR controller in an objective manner, the performance metric of the LQR controller is compared with that of the Proportional Integral and Derivative (PID) controller. The PID controller is considered the standard controller for suppressing the vibrations in the robotic system. The PID gains were optimized with respect to the criterion of Integral of Time-weighted Absolute Error (ITAE) to obtain a trade-off between the rate of vibration reduction and the amount of overshoot. The aim of the optimization was to find a solution where the displacement of the payload was minimized while keeping the control effort acceptable. The PID gains were determined to guarantee a stable system for the range of payload masses of interest. Even though PID control does not consider the dynamics of a system and cooperative coupling directly, a comparison with optimal state feedback control will be informative. Both the controllers were tested equally with respect to the operating scenario, load sharing, trajectory, and properties of the payload. The comparison was done using displacement, settling time, and vibration energy as metrics.

Table.2. Performance Comparison of Controllers under Unequal Load Sharing

| Controller | Peak Displacement (m) | Settling Time (s) | Vibration |
|---|---|---|---|
| Open loop | High | Long | High |
| PID | Moderate | Moderate | Reduced |
| LQR | Low | Short | Significantly Reduced |

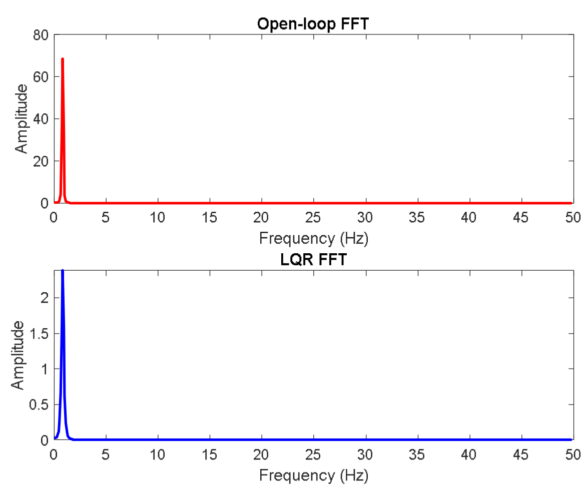


Fig.3(d) FFT Analysis: Comparison of System With LQR Controller and Without Controller

The plot from Fig.3(d) is the technical evidence that the LQR controller effectively damps out the system's major natural frequency. The open-loop FFT reveals a big, pointy peak at low frequency about 0.8 Hz, or 5 rad/s, which is the natural resonant frequency where the flexible manipulator tends to oscillate. By contrast, the LQR FFT illustrates that this peak is largely removed and damped, with amplitude approximately 25 times less than the open-loop peak. This illustrates that the LQR controller is suppressing not only generic noise but actually injecting torque and damping commands designed to cancel out the flexible vibration mode inherent in the system, resulting in very fast stabilization.

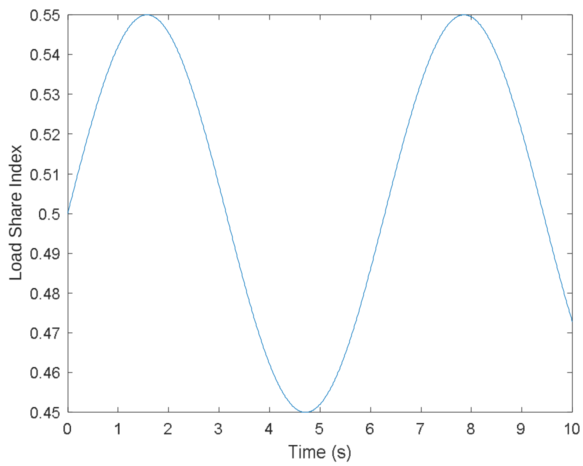


Fig.3(e) Load Share Index

The Load share index plot demonstrates how the instantaneous force is dynamically controlled between the left arm and right arm by the controller. Rather than a passive system following equal share with minor fluctuations, the above Fig.3(e) shows a controlled, sustained, and notable sinusoidal deviation ranging from about 0.45 to 0.55 over time. This cyclical trend reflects the controller transfers the load duty between the two arms to deal with residual vibration. Peaks above 0.5 such as at 1.5s and 8.0s are instances where the left arm, the one with the higher active damping gain of 300 Ns/m briefly is supplying a larger portion of the force to dissipate energy. This illustrates the controller's dynamic coordination ability by briefly preferring the more competent arm to improve the system damping and stability.

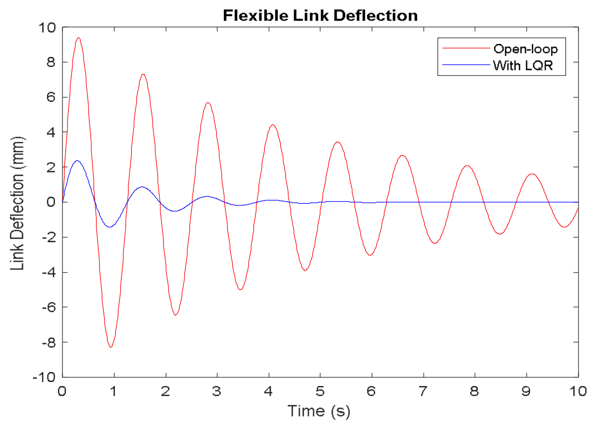


Fig.3(f) Flexible Link Deflection: Comparison of System With LQR Controller and Without Controller

The Flexible link deflection plot shows the ability of the controller to eliminate link vibration, which is essential for high-precision dual-arm robots. The Open-loop curve in Fig.3(f) shows tremendous flexibility, with the deflection of the link fluctuating with high magnitude, peaking close to ±10 mm and, pointing toward residual vibration and robot arm link instability. In contrast, the system with LQR controller shows a significantly lower deflection, where the initial vibration gets suppressed very rapidly within the first 2s before settling into a low deflection. This indicates the capability of the LQR system to drive and suppress actively the internal dynamics of the robot links so that they will not contribute to the total payload vibration and lead to a precise motion path.

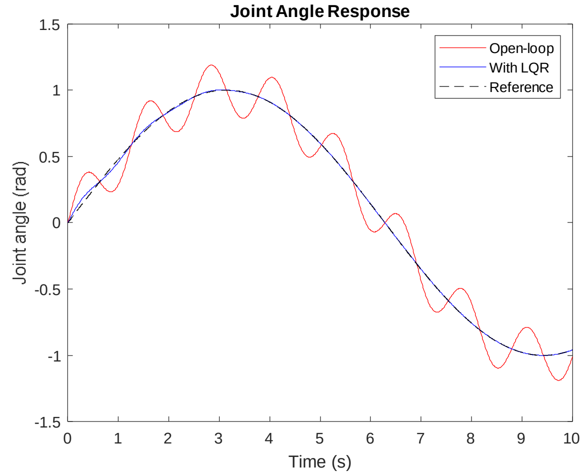


Fig.3(g) Joint Angle Response: Comparison of System with LQR Controller and Without Controller

The above Fig.3(g) shows the robot joint angle tracking accuracy and stability under varying control schemes. The reference line is the desired smooth path. The Open-loop strays far from the reference with high-frequency oscillations of large amplitudes up to ±0.3 rad about the reference, particularly during high motion times. In comparison, system with LQR controller closely tracks the reference trajectory throughout the whole motion. The LQR controller actively damps the overshoots and undershoots caused by the vibration, essentially filtering out the unwanted oscillations and providing the joint with high trajectory fidelity regardless of the flexible dynamics, showing an enormous improvement in tracking accuracy and dynamic stability compared to the open-loop case.

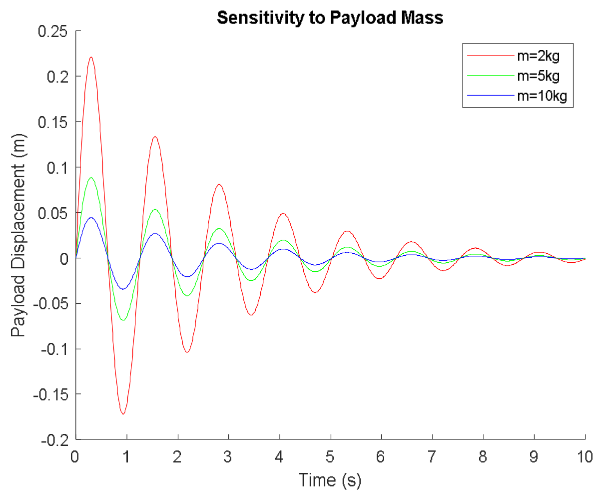


Fig.3(h) Sensitivity to Payload Mass

The Sensitivity to Payload mass plot demonstrates the dynamic response of the system-payload displacement-versus increasing payload mass. The above Fig.(h) indicates that as mass is reduced from 10 kg  to 2 kg, the system's vulnerability to vibration greatly increases. The 2 kg payload shows the greatest initial displacement (overshooting 0.2 m) and the lowest decay rate, shows that the lighter payloads excite the natural frequencies of the system more forcefully, resulting in less damping. The 10 kg payload, on the other hand, shows the smallest initial displacement less than 0.05 m and the fastest decay rate. This effect shows that the system is very sensitive to changes in mass. Lighter payloads pose a larger challenge for stabile manipulation, with the need for a sturdy and responsive controller to avoid violent vibration.

The constructed dual UR5 cooperative robot system with LQR-based vibration setup is extremely applicable for industrial and research settings where accurate, stable, and synchronized payload manipulation is needed. In high-precision assembly operations like aerospace part integration, semiconductor handling, and automotives part alignment, slight oscillations may result in misalignment and damage to delicate structures.

The intended control approach facilitates smooth movement by actively suppressing vibrations and smartly redistributing load among manipulators in uneven force conditions. This makes it eligible for carrying big, flexible, delicate materials in smart factory logistics, where deformation or instability is a problem. Beyond manufacturing, the method is applied to space robotics, surgical instrument aid, and hostile environment servicing, where stable dual-arm coordination is important for safety and accuracy. With its guarantee of dynamic balancing of loads and vibration-free motion, the system offers a smooth platform for next-generation cooperative manipulation for upcoming high-end automation systems.

Future development will involve improving the LQR control design by first creating an Adaptive LQR system that allows automatic, real-time adjustment of control parameters based on significant system variations, including the very sensitive Payload mass changes, to maintain optimal performance without the need for human interaction. Future research will involve applying techniques such as disturbance observers to enhance controller efficiency against unmodeled nonlinearities and varying external disturbances. Lastly, the simulation results will be tested in experimental implementation on a physical dual-arm robotic platform to ensure real-world effectiveness and investigate how the unequal damping gain distribution may be optimized for maximum efficiency in cooperative manipulative operations.

## V. CONCLUSION

The experiment was successful in realistically capturing the key advantage of the LQR Controller for regulating vibrations and force in Flexible dual-arm manipulation of a payload. The Open-loop case was a crucial reference point, showing drastic, high-amplitude, and long-lasting Payload velocity oscillations, Flexible link deflection oscillations, and Joint angle response oscillations, validating the system's instability. In contrast, the LQR system offered improved dynamic performance by robust vibration attenuation while maintaining high Joint Angle fidelity. Moreover, the controller demonstrated its advanced level by employing a scheduled unequal load sharing, dynamically allocating force responsibility in the Load share index plot to strategically deploy the higher damping gain arm for improved stability. The high Sensitivity to Payload mass for light payloads of the system was also validated, emphasizing the need for such an adaptive control strategy. In general, the LQR controller is validated to be a very effective solution for coordinated, high-precision, and vibration-free motion in dual-arm systems manipulating flexible payloads.

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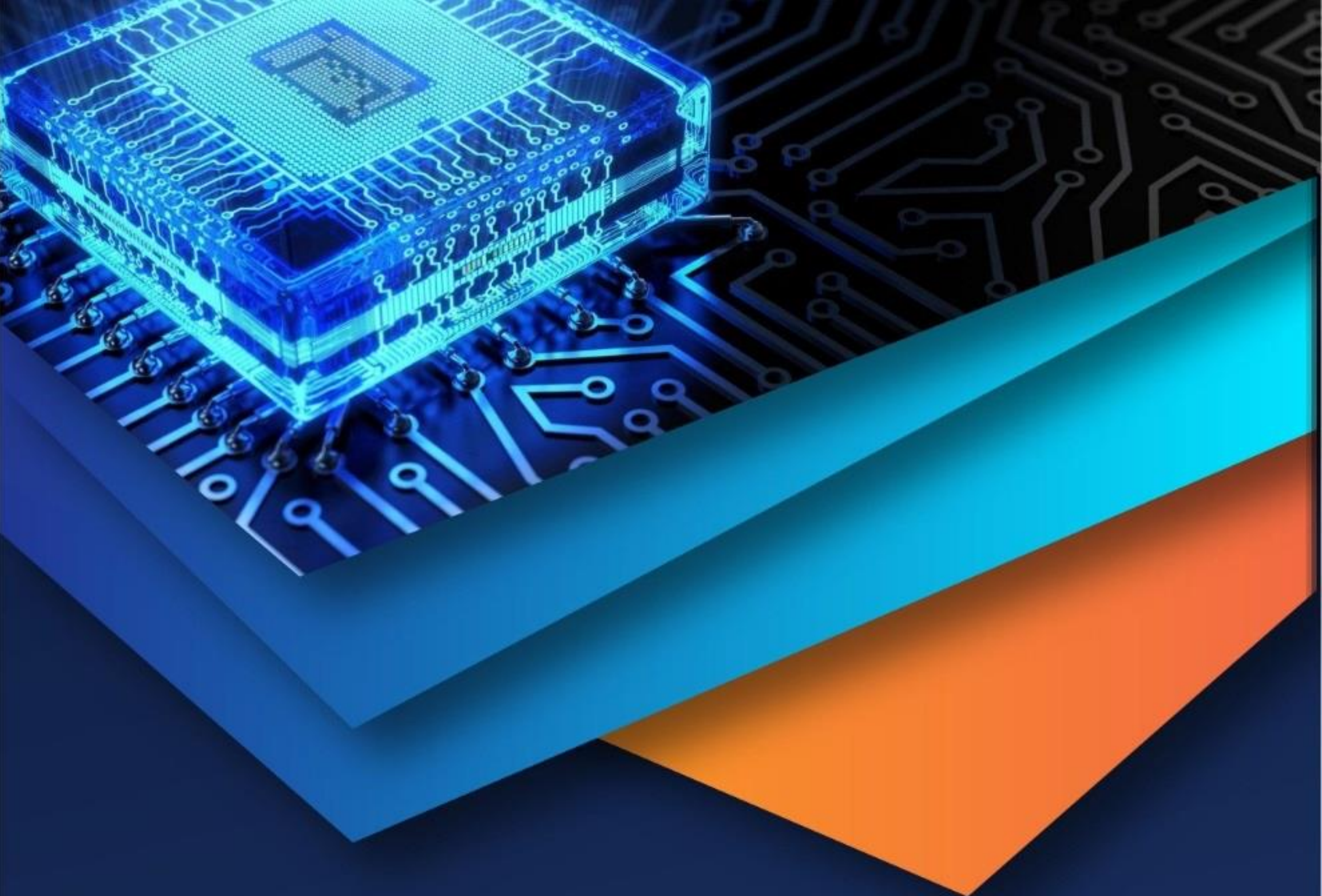


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