IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Comparative Analysis Of Different Dynamic Control Strategies For Robotic Manipulator

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Abstract: This research study presents a comparative analysis of various dynamic control strategies for robotic manipulators. The study investigates and evaluates different control approaches, including feedback linearization, computed torque control, passivity-based control, among others, in terms of their performance characteristics. Through simulation studies and experimental validations, the effectiveness of each control strategy is assessed with respect to trajectory tracking accuracy, disturbance rejection capability, energy efficiency, computational complexity, and adaptability to changing operational conditions. The research also highlights the trade-offs and limitations of each control strategy, offering valuable insights into their practical applicability in real-world robotic systems. The findings of this study aim to provide guidance for engineers and roboticists in selecting the most appropriate dynamic control strategy for specific manipulator applications, thereby contributing to the advancement of robotic manipulation technologies.

***Index Terms* -** Adaptive Control, Computed Torque Control, Computational Load, Dynamic Control Systems, Feedback Linearization, Nonlinear Dynamics, Parameter Adaptation, Passivity-Based Control

I. INTRODUCTION

Within the field of robotics, and more specifically robotic manipulators, there is an ongoing goal to improve the dynamic control of these devices in a way that optimizes the efficiency, accuracy, and adaptation of their movement and interaction with tasks. The dynamic control of robotic manipulators is an important aspect that can have significant influence on efficiency, accuracy, and adaptation of their behavior. Therefore, in the goal of improving science or science and technology related to robotics manipulation, this research will study and provide a comparative study of some of the most popular dynamic control systems in robotic manipulators.

The control strategies that will be the focus of this research includes a range of control strategies that are designed to improve trajectory tracking, distortional rejection, energy efficiency, computational efficiency, and overall stability of the control system while facing a variety of dynamic conditions. Thus the focus on strategies such as passivity-based control, computed torque control, and feedback linearization will be studied to contribute to control performance properties and constraints of the dynamic controllers.

There are various control strategies that are commonly adopted in the dynamic control of robotic manipulators Feedback Linearization approach relies on transforming the robotic manipulator's nonlinear dynamics into a linear format through utilization of a suitable feedback control law; thus, rendering it possible to manage the system's nonlinearities and, in turn, simplifying the controller design that permits state trajectory tracking and disturbance rejection, which do beset many nonlinear control laws. Computed Torque

Control also known as inverse dynamics control, computed torque control computes the torque inputs required to achieve the desired manipulator motion while accounting for dynamic nonlinearities (inertia, etc., and gravitational effects). Computed torque control systems allow for accurate tracking of the desired trajectory and robust performance in the presence of dynamic uncertainty. [4] Passivity-Based Control method exploit energy passivity to design control laws that ensure desired dynamic robot manipulators robustly perform with these uncertainties. Passivity is a defined energy property that incorporates energy shaping. Passivity-based control design can enable stable dynamic manipulator performance when the manipulator payload typically destabilizes the energy balance. Adaptive Control design has favor in handling uncertainties and variations in the dynamic properties of robotic manipulators. Adaptive control laws change online using parameter adaptation techniques that account for the varying manipulator dynamics. In these cases, system modelling can be inconvenient or uncertain, mitigating the effects of dynamic manipulator parameter variability is useful.

I. FEEDBACK LINEARIZATION

Feedback linearization is one of the promising approaches to nonlinear systems, particularly the robot manipulators. It makes the design of the control easier since the system dynamics involve transforming the nonlinear system into a linear structure more easily handled using conventional linear control techniques.[1]

Few applications of feedback linearization are listed below Precise Trajectory Tracking, feedback linearization technique is mainly used to accomplish an accurate trajectory tracking in robotic manipulators. The manipulation of the nonlinear dynamics into a linear model enables the use of regular linear controller to achieve high performance in maneuverability hence suitability in pick-and-place functions, assembly, and complicated path tracking, Disturbance Rejection of the two, feedback linearization improves the system's performance in rejecting disturbances. After linearizing the system, it became possible to derive control laws capable for eliminating external disturbances such as forces in the vicinity of the manipulator not modeled into the system. This has the benefit of bringing better robustness, and the capacity to confront unexpected changes in the company's environment, Complex Manipulator Configurations, In machines having manipulators, which are characterized by complex nonlinear dynamic equations feedback linearization effectively alters the control problem. This is advantageous to the controller since the system can then be approximated to be linear simplifying the control design especially where the system exhibits nonlinear behaviours due to modeling or control difficulties.[2]

The other benefit of the closed-loop feedback linearization is the problem of putting a law of control into practice since it is quite easier to put more effort designing controllers of systems which are already in the linear form than to struggle with the nonlinear form of the same system. In addition to greatly reducing the design complexity, this approach also consistently improves trajectory following and noise suppression and other aspects of the system's stability. Also, feedback linearization is generally preferable to a straightforward attempt at controlling the nonlinear plant since the former gives superior performance to the latter.

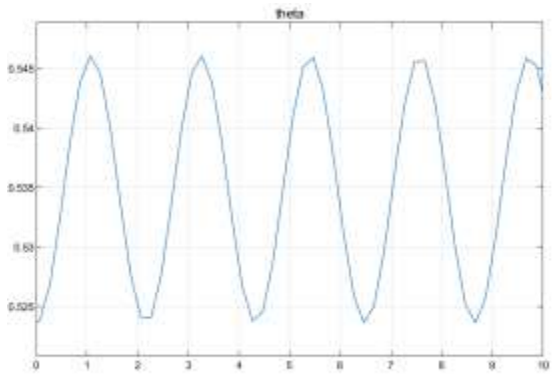

Fig 1. Periodic Oscillatory Response of Theta over Time

Fig 1 shows a periodic oscillatory response of theta over time. This indicates that the feedback linearization control method is able to achieve a stable, periodic motion of the manipulator joint angle theta. Therefore it is not stable and oscillatory.

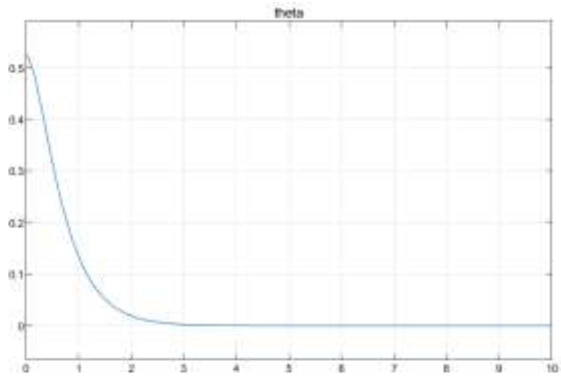

Fig 2. Convergence of Theta to Steady-State Value

Fig 2 shows the theta response decaying over time, approaching a steady-state value. This suggests that the feedback linearization control is able to stabilize the manipulator joint angle theta and drive it to a desired setpoint or equilibrium position. Therefore it becomes asymptotically stable after implementing feedback linearization law.

II. COMPUTED TORQUE CONTROL

Computed torque control also known as inverse dynamics control is one of the most important control techniques that provides direct consideration of the robotic manipulator dynamics inclusive of inertia, Coriolis and gravitational forces. This control method determines the torque inputs it needs to get accurate and smooth motion of the manipulator.

Few applications of computed torque control are listed below High Precision Tasks Computed torque control found most appropriate in those system that demand high level of accuracy and precision. It determines how the manipulator is actually moving and then subtracts the motion that is wanted, and then applies the torque necessary to minimize the difference. This makes it very suitable for point to point transfers that are very crucial in activities such as assembly, machining, and surgery. Thus, computed-torque control is less sensitive to the errors of linear control methods when it comes to fine motion tasks, as would be expected from a Swiss army knife. Dynamic Environments where reference trajectory varies due to factors such as instability or uncertainty, the computed torque control can counter outside hectors and torques. Through the use of real-time dynamics compensation, this approach guarantees that the manipulator is able to operate optimally regardless of the loads it has to carry or any and all external interferences. This capability makes it useful in application where a manipulator must function dependably when fed signals that are vary with time as seen in manufacturing, space and hazardous activities. Flexible Manipulator Configurations in this way, computed torque control can be generalized for manipulators with great number of degrees of freedom or intricate structure. Incorporation of the dynamic model of the system into the control algorithm enhances its effectiveness in controlling different types of manipulators. This makes it appropriate for a wide range of robotic structures, from industrial, medical and research robotics structures where mechanical arrangements and functional necessities vary. [3]

Compared to computed torque control directly decomposing the rigid nonlinearities specific to robotic systems, the overall control performance is further promoted, especially in high precision operational tasks. Compared to the linear control methods, the computed torque control is more versatile due to the application of different manipulator configurations and dynamic specifications. Closely related, this versatility of function expansion across different and possibly complex robotic platforms also greatly accounts for its application in modern sophisticated robotics, where the requirement for fine and stable control is often paramount.

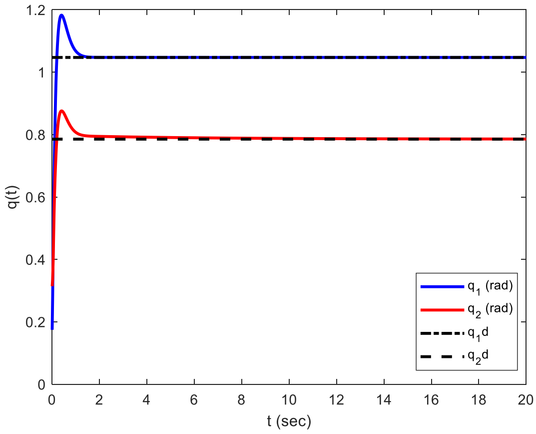

Fig 3. Critically Damped Response of Theta under Computed Torque Control

Fig 3 displays a rapid rise in the theta value, followed by a sharp decline and then a gradual convergence towards a steady-state value. This behavior is characteristic of a critically damped or overdamped system response, where the system quickly reaches the desired setpoint without any oscillations or overshoots. From these observations, we can conclude that the computed torque control method is effective in controlling the motion of the manipulator joint angle theta. The rapid rise and subsequent convergence to the steady-state value demonstrate the ability of this control technique to achieve the desired manipulator joint angle trajectory in a stable and efficient manner. The error between the actual trajectory and the desired trajectory is just 10^-3 to 10^-4 radians which is very small and negligible.

III. PASSIVITY-BASED CONTROL

Passivity-based control (PBC) is a control method that uses the concept of passivity to control interactions of a system; it concerns itself with energy exchange to guarantee sound stability and robustness. They have become useful approach in the wide range of fields because of the ability to ensure the particular closed-loop characteristics, like stability or safety.[7]

Few applications of Passivity-based control are listed below Energy Shaping and Dissipation, PBC is most effective where there – are tasks typified by handling and control of energy in a system. Thus, this approach enables the fine tuning of energy storage density, energy dissipation mechanisms, and energy recycling inside the envisioned electronic materials. Such uses are intelligent braking in electrical vehicles, storage devices, and mechanical systems that must achieve oscillation through energy destruction such as robotic mechanical parts that are required to dampen shocks or vibrations. Physical Human-Robot Interaction, in situations where robots share their space with people passivity based control makes the robot passive therefore it does not initiate extra energy into the interaction flow. This leads to more natural and safe operating interaction between people and robots especially in areas like health care robotics or rehabilitation robotics or even manufacturing systems that involves cooperation in between human and robots. Stability in Networked Systems, hence, PBC is well suited to other networked control scenarios such as a multi-agent robotic control, distributed sensor networks and other cyber physical systems. As a result, the amount of energy for the interconnected parts is controlled, which in turn results in improved system stability & reliability. This is important in such systems where close interacting of several sub systems or autonomous agents is required to be stable in a changing context like fleet of autonomous vehicles or large-scale sensor networks. However, due to the fact that PBC developed based on the passivity theory, it has the advantage of inherent stability focusing on distribution and load handling which performs robust against interferences and noise. This robustness is especially advantageous in systems where stability under these conditions is essential, such as power systems or dynamic robots which must balance against loads. Moreover, PBC is highly effective when an environment or a system experiences rapid changes: PBC may be useful in the circuits of industrial plants with stochastic loads or autonomous systems in the conditions of variable loads. Due to its consistency with decentralized and distributed control, PBC can be beneficial for systems with loosely coupled subsystems where every component can sustain passive behaviour on its own, which is useful for applications such as in smart grids and multiple robot systems where global structure integrity must be maintained. In addition, the energy supply and the control of the consumption are very efficient in PBC that encourages the energy conservation, this is rather important for the battery operated robots, the energy scavenging systems and photovoltaic energy systems that highly prioritize efficiency.[6]

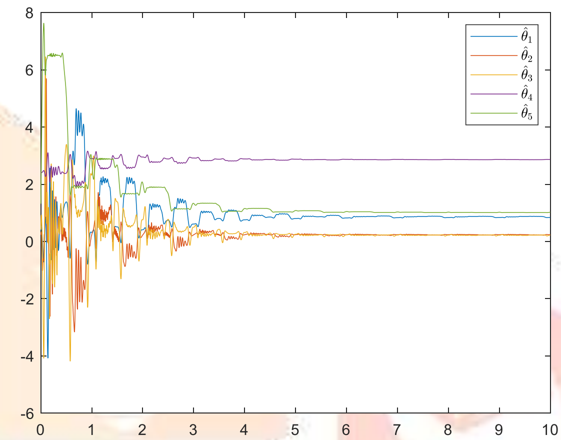

Fig 4. Periodic, oscillatory response for the joint angles

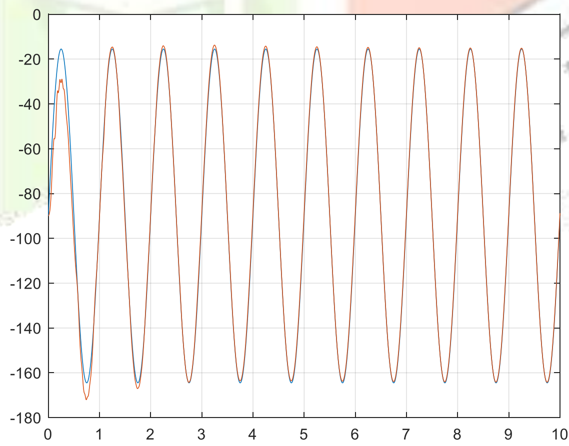

Fig 5. Periodic, damped response for the joint angles

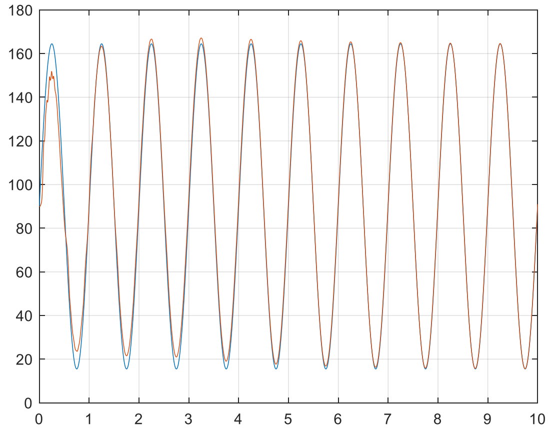

Fig 6. Stabilizing effect of the passivity-based control

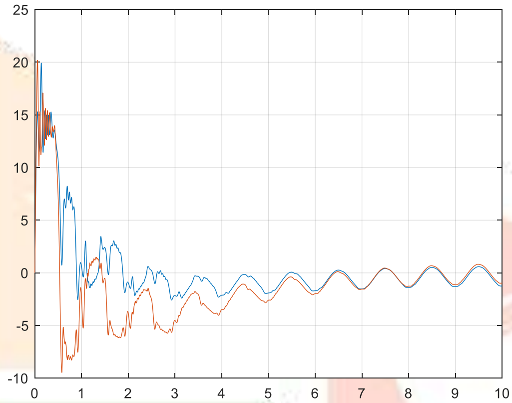

Fig 7. Complex joint angle responses, with larger initial transients and oscillations

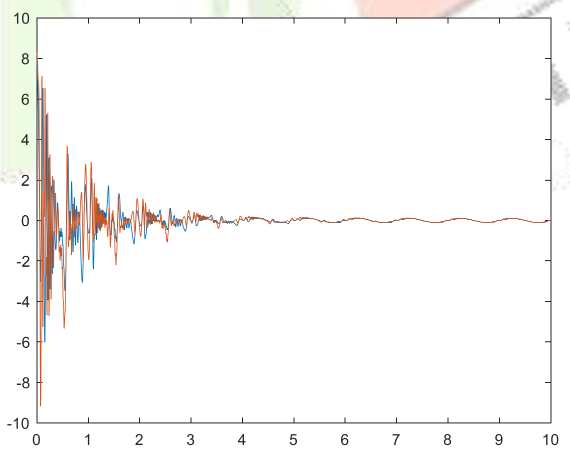

Fig 8. Converging towards a steady-state over time

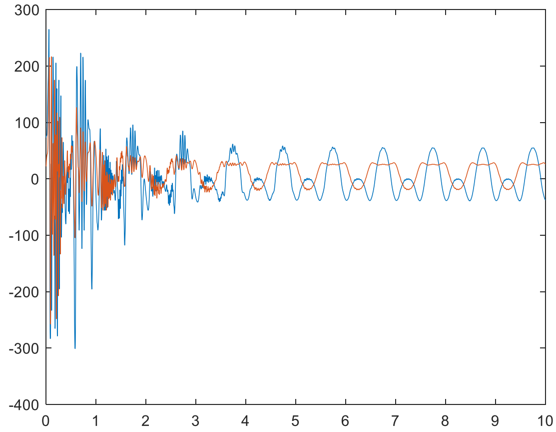

Fig 9. Theta response

Fig 4 shows a periodic, oscillatory response for the joint angles, with the amplitude of the oscillations decreasing over time. This indicates that the passivity-based control method is able to stabilize the manipulator joint angles and drive them towards a steady-state condition.

Fig 5 and Fig 6 display a similar periodic, damped response for the joint angles, further confirming the stabilizing effect of the passivity-based control.

Oscillatory Behaviour: Both the lines exhibit periodic behaviour over the x-axis range of 0 to 10. This indicates that the system has an oscillatory response, which is typical in systems where energy is being transferred back and forth.

Amplitude and Damping: The system representing the blue line oscillates with a smaller amplitude, ranging approximately from -20 to -100, while the system representing the orange line has a larger amplitude, ranging from 0 to -180. This suggests that the blue line represents a more damped response, meaning it loses energy more quickly and stabilizes faster. In contrast, the orange line indicates a less damped or more energetic response, with larger oscillations

Fig 7 and Fig 8 show more complex joint angle responses, with larger initial transients and oscillations, but still converging towards a steady-state over time.

Fig 9 provides a more detailed view of the theta response, clearly demonstrating the periodic, damped behavior observed in the previous graphs.

Based on these observations, we can conclude that the passivity-based control method is effective in controlling the manipulator joint angles, as it is able to stabilize the system and drive the joint angles towards their desired steady-state values, despite the initial transient responses.

IV. ADAPTIVE CONTROL

Adaptive control is one of the strongest approaches intended for control of systems that either have unknown, unpredictable, or varying characteristics. It designs its parameters on admission to act on actual information and as such is subject to operate on nonlinear procedures hence is relevant in command of heaped up odd functions and conditions whereby straightforward command would not operate.[8]

Few applications of Adaptive control are listed below Unknown or Time-Varying Dynamics, adaptive control is especially useful for the systems that where the characteristics of the system are unknown, a priori or are time-varying. Due to this, controllers can monitor changes in the dynamics of the system; best used in applications where such dynamics tend to vary with time. These are for instance procedural structures that undergo deformation for instance flexible aerospace parts as well as systems that work in interaction rates such as underwater vehicles or biological systems. Fault Tolerant Control, one of the major functions of an adaptive control system is realized of failure-tolerant systems. When abnormalities emerge in the parameters of a system, or in its environment, adaptive control offers the facility to restore its operation. This makes it very suitable for use in safety related applications like car manufacturing, Aircraft flight control, and production industries where failure of the system leads to disastrous circumstances. Uncertain Environments, there are usually high uncertainties when it comes to operating conditions and therefore; adaptive control systems work best by constantly adapting to this environment. For instance, mobile robots or self-driven car's traveling in rough environment and often changing conditions which will greatly benefit from adaptive control. Such systems can respond to changes in the friction coefficient of the contact surface, the presence of obstacles or inclinations of the actual terrain, which contributes to the improvement of the reliability of Actions. Nonlinear Systems it is also a principle in dealing with systems that cannot be governed by the standard linear control system, which has its methods limited in nature. As it adapts control parameters depending on the state of the system, it finds application in nonlinear plants like industrial robots where give increase in load or change in structure alters the characteristics of the plant.

In addition, Robustness to Uncertainties Adaptive control also adds flexibility so that a system can deal with variations and he unforeseeable which other forms of control cannot contain. This makes system performance reliable because it can retain system performance and stability in the face of varying system dynamics or external conditions. Improved Performance Under Varying Conditions since control parameters are re-calculated periodically, adaptive control guarantees an efficient operation of the system under different operations contexts. To simplify, it is best for systems that may be expected to work across different settings or when loads vary significantly, like in industrial equipment, drones, or self-driving cars. Real-Time Adaptation the fact that adaptive control systems are able to gain sufficient control in real time is one of the greatest strengths within the controllability of a number of systems as the majority of such systems have dynamics which are almost impossible to predict beforehand. Whenever system behavior is somewhat probabilistic, such as with fluids or in biological queries, adaptive control is possible to keep the system running optimally despite the uncertainty. Challenges in Convergence and Stability, Indeed adaptive control possesses certain limitations such as a difficulty in achieving stable convergence. The possibility exists that the system may take too long to adapt appropriately, adapt too fast, or worse still, equilibrium may be reached at undesirable parameters. The convergence speed and tracking performance then depend on a vector of adaption which has to be be designed very carefully to ensure stability does not become an issue. This issue becomes particularly critical when implementing adaptive control of safety related or systems that depend on the specified precision.[9]

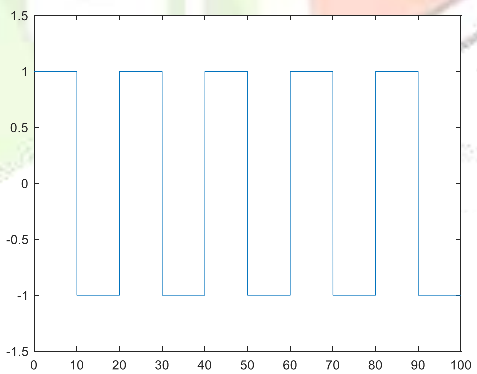

Fig 10. Position error over time

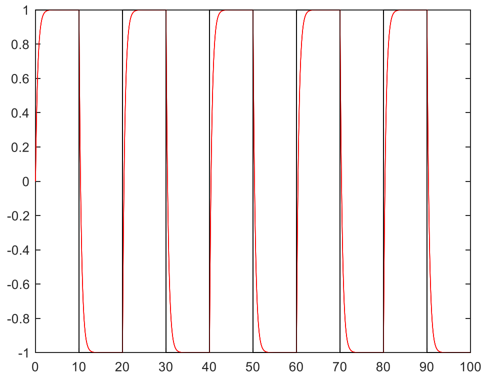

Fig 11. Control input over time

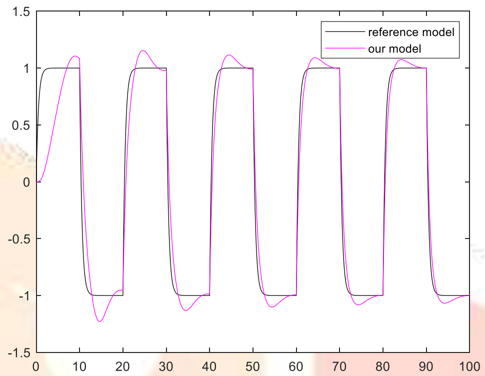

Fig12. Adaptive parameters over time

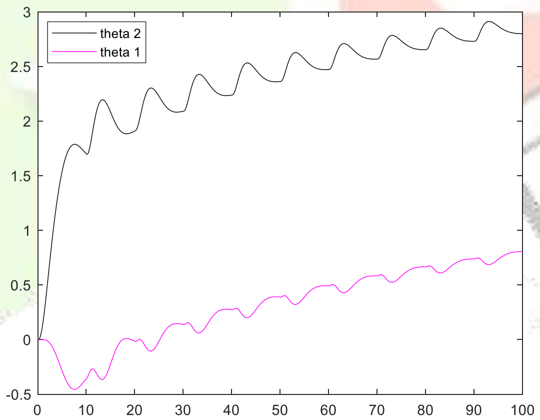

Fig 13. Desired and actual trajectories of the manipulator

The graph exhibits a series of spikes, indicating that the position error is fluctuating significantly. This suggests that the adaptive control method may not be providing a smooth and stable control of the manipulator's position as shown in Fig 10. Fig 11 shows the control input over time. The control input appears to be oscillating between positive and negative values, which could be a result of the adaptive control algorithm trying to compensate for the position errors. The adaptive parameters are also exhibiting oscillatory behavior, which could be a reflection of the instability or sensitivity of the adaptive control algorithm. As shown in Fig 12. Fig 13 shows the desired and actual trajectories of the manipulator. The actual trajectory appears to be closely following the desired trajectory, but there are still some deviations, especially in the regions with higher curvature.

CONCLUSION

Feedback linearization provides a means to reconfigure the nonlinear dynamics of a system into a linear form, facilitating precise trajectory tracking, disturbance rejection, and control of complex manipulator configurations. Computed torque control, or inverse dynamics control, excels in achieving accurate trajectory tracking, robustness, and stability, especially for manipulators with dynamic environments and complex configurations. However, its computational complexity warrants careful consideration. Passivity-based control focuses on energy management, enabling efficient dissipation and shaping of energy flows within a system. Its applications include human-robot interaction, stability in networked systems, and tasks requiring energy management and dissipation. Adaptive control, with its real-time parameter adjustment, is well-suited for systems with unknown or time-varying dynamics, allowing for fault-tolerant control, adaptation to uncertain environments, and control of nonlinear systems. This research study presents a comparative analysis of various dynamic control strategies for robotic manipulators. The study investigates and evaluates different control approaches, including feedback linearization, computed torque control, passivity-based control, among others, in terms of their performance characteristics. Through simulation studies and experimental validations, the effectiveness of each control strategy is assessed with respect to trajectory tracking accuracy, disturbance rejection capability, energy efficiency, computational complexity, and adaptability to changing operational conditions. The research also highlights the trade-offs and limitations of each control strategy, offering valuable insights into their practical applicability in real-world robotic systems. The findings of this study aim to provide guidance for engineers and roboticists in selecting the most appropriate dynamic control strategy for specific manipulator applications, thereby contributing to the advancement of robotic manipulation technologies.[10]

REFERENCES

[1] Mark W. Spong(1989)Feedback Linearization of Robot Manipulators,IEEE Transactions on Automatic Control 654-660

[2] M. F. Fahmy and H. A. Moustafa (2006)Robust Feedback Linearization Control of Robot Manipulators, International Journal of Control,575-589

[3] K. T. Shih and M. W. Spong (1992)Adaptive Computed Torque Control of Robot Manipulators IEEE Transactions on Robotics and Automation 193-198

[4] Author: G. Oriolo, A. De Luca, and F. Siciliano(2004) Control of Robot Manipulators: A Unified Approach In Robotics Research: The Eleventh International Symposium 177-188

[5] Sciavicco, L., & Siciliano, B. (2012). Modelling and control of robot manipulators. Springer Science & Business Media.

[6] E. Cataldi, A. Macchelli, and C. Melchiorri (2009), A Passivity-Based Control Approach to Physical Human-Robot Interaction IEEE International Conference on Robotics and Automation (ICRA),3974-3979

[7] N. Chopra, M. W. Spong, and R. Lozano(2006)Passivity-Based Control of Robotic Systems,Springer 75-110

[8] Ioannou, P. A., and Sun, J.(1996)Robust Adaptive Control, IEEE Transactions on Automatic Control,1453-1463

[9] L. Y. Wang and G. G. Yin (2006)Adaptive Control of Nonlinear Systems with Uncertain Dynamics, IEEE Transactions on Automatic Control 553-568

[10] Mark W. Spong (1989) Robot Dynamics and Control,Wiley,125-165