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Semantic Web-Driven Hybrid Adaptive Control System for Trajectory Tracking in Robotic Arms

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ABSTRACT

In modern industrial production, trajectory tracking control of multi-degree-of-freedom robotic arms entails safety and efficiency. This study focuses on a two-degree-of-freedom manipulator, developing a mechanical dynamics model and implementing a parallel Linear Active Disturbance Rejection Controller (LADRC) for joint control. To enhance robustness and responsiveness, a hybrid adaptive control method is introduced, integrating adaptive laws (AL) for online tuning of parameters and offline optimization using the Deep Deterministic Policy Gradient (DDPG) algorithm. This improves tracking control efficiency and effectiveness. Additionally, offline reinforcement learning refines parameters without adding real-time computational demands. Finally, semantic web principles ensure interpretability and transparency of the control flow. Compared to traditional LADRC, the proposed method shows superior anti-interference capabilities and dynamic performance.

KEYWORDS

Linear Active Disturbance Rejection Controller, Deep Deterministic Policy Gradient Algorithm, Hybrid Adaptive Control, Multi-Degree-Of-Freedom Robotic Arms

INTRODUCTION

The rapid advancement of technology has driven the widespread use of robots in industrial and everyday applications. Robotic arms, valued for their flexibility, are extensively employed in industry; however, this flexibility complicates the mathematical modeling of series manipulators. Achieving precise trajectory tracking of multi-degree-of-freedom manipulators is essential to ensure safety and efficiency in industrial production. This involves minimizing position and trajectory errors, avoiding operator risks from instability (Mendrofa & Muis, 2021), and preventing fatigue-induced damage in complex environments (Zhang et al., 2021). Recent developments in semantic trajectory planning further enhance the accuracy and productivity of industrial robots by improving their navigation in dynamic environments (Li et al., 2024).

The Active Disturbance Rejection Controller (ADRC) has gained significant scholarly attention for its independence from model information, simple structure, and ability to address coupling and nonlinearity (Han, 1998, 2009). Building on this, Gao (2013, 2014) introduced Linear ADRC (LADRC) in 2013 and 2014, which employs a Linear Extended State Observer (LESO) for disturbance

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estimation and a proportional-derivative control law for disturbance rejection. LADRC simplifies complex nonlinear systems into manageable linear forms by compensating for total disturbance, making it widely applicable due to reduced parameter requirements.

Despite its linear structure, LADRC effectively handles nonlinear systems with minimal dependence on system models (Huang & Zhang, 2002). Its theoretical stability has been extensively studied (J. Song et al., 2022), with applications in power systems (Sun et al., 2022), robotics (Li et al., 2021; Sinan, 2024), and aircraft control (Lin et al., 2023; T. Yang et al., 2023). Given its strengths, LADRC is well-suited for robotic arm path tracking under moderate environmental demands. This article proposes an enhanced strategy for LADRC to further improve its performance.

A high-quality controller must not only ensure superior control performance but also exhibit robust anti-interference and adaptive capabilities to address dynamic environmental changes. W. Yang et al. (2023) proposed improving observers in Deep-Reinforcement-Learning-based controllers, while Liu et al. (2019) and Yang et al. (2021) emphasized adaptive control laws using piecewise monotonic functions for parameter adjustments based on error intervals. Zheng et al. (2021) integrated Deep Q-Networks with ADRC for real-time parameter tuning, and W. Song et al. (2022) explored online reinforcement learning for dynamic LADRC parameter modification. Similarly, Zheng et al. (2023) adopted a Deep Deterministic Policy Gradient (DDPG) approach.

Controller parameter tuning remains a challenge, with optimization algorithms increasingly replacing manual adjustments, offering time-efficient solutions (Guo et al., 2023). Considering the critical role of parameter selection, this article utilizes offline reinforcement learning for controller parameter optimization. Semantic trajectory planning has also advanced industrial robots' navigation in complex environments. However, challenges, such as the black-box nature and reliability of machine learning models, persist. Integrating semantic web interfaces to provide explanatory feedback can enhance system interpretability (Malhotra et al., 2022). Previous studies have shown that semantic web technology can significantly improve the interactivity and interpretability of control systems (Chhetri, 2021).

Research and practical applications show that online reinforcement learning can dynamically adjust control parameters in changing environments, offering benefits like adaptability, model independence, and the ability to handle complex scenarios. Research shows that reinforcement learning contributes to solving robot kinematics and inverse kinematics control, highlighting its broad potential for applications in robotics (Tutsoy, 2015; Tutsoy et al., 2017). However, it faces challenges like low learning efficiency, high computational costs, and difficulty balancing exploration and exploitation (Asl & Uchibe, 2023; Gao et al., 2022). In practical applications, real-time performance and security are paramount. While adaptive laws require fewer computational resources than online reinforcement learning and avoid iterative calculations (Alhazmi & Sarathy, 2023), their performance heavily depends on proper parameter selection. To address these limitations, this study proposes a hybrid adaptive control strategy that integrates offline reinforcement learning for optimal parameter training with online adaptive laws to manage disturbances in real-time environments effectively.

The main contributions of this article can be outlined as follows:

- Integration of a bandwidth-adaptive control law into the traditional LADRC framework, enabling dynamic adjustment of controller parameters on the contrast with the offline DDPG-LADRC.
- Application of offline reinforcement learning to jointly optimize controller and adaptive law parameters, ensuring smooth transitions in dynamic environments. This results in a hybrid adaptive control architecture where components complement and enhance each other.

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