Abstract

Energy consumption is a critical concern in industrial robotic systems due to increasing operational costs and the demand for sustainable manufacturing. Conventional trajectory planning methods for industrial robot manipulators primarily focus on motion smoothness and time efficiency, often neglecting energy usage during task execution. This study investigates energy-efficient trajectory planning for a 6-DOF industrial robot manipulator using a physics-based simulation approach.

Classical cubic and quintic polynomial trajectories are compared with an energy-optimized trajectory designed to minimize total energy consumption. Joint torque and angular velocity are used to compute instantaneous power and total energy. All trajectories are evaluated under identical task conditions using the PyBullet physics-based simulator, which provides realistic dynamic behavior. Simulation results demonstrate that the proposed energy-optimized trajectory significantly reduces energy consumption and peak joint torque compared to classical methods, while maintaining acceptable task execution time. The findings confirm that physics-based simulation is an effective tool for evaluating energy-efficient robot motion planning strategies.

This study provides guidelines for designing energy-efficient motion plans in industrial manipulators, contributing to sustainable manufacturing, reduced operational costs, and improved actuator longevity.

Introduction

Industrial robot manipulators are widely used in manufacturing industries for tasks such as assembly, welding, and material handling. Trajectory planning plays a critical role in determining robot motion by defining joint positions, velocities, and accelerations over time. Traditional trajectory planning approaches are primarily designed to ensure smooth motion and accurate task execution within a specified time.

Although these approaches are effective for motion control, they often overlook energy consumption during robot operation. High energy usage not only increases operational costs but also induces mechanical stress on joints and actuators, reducing system efficiency and lifespan. As industries move toward sustainable and energy-aware production systems, reducing the energy consumption of robotic manipulators has become an important research topic.

Several studies have proposed energy-related optimization techniques for robotic motion. However, many of these works rely on simplified dynamic models or lack validation under realistic physical conditions, resulting in reported energy savings that may not accurately represent actual industrial robot behavior. Classical polynomial trajectories such as cubic and quintic methods provide smooth motion but do not directly consider energy minimization.

Physics-based simulation offers a practical solution to this limitation by incorporating realistic dynamics, joint constraints, and actuator behavior. This research investigates energy-efficient trajectory planning for a 6-DOF industrial robot manipulator using a physics-based simulation framework. Classical polynomial trajectories are compared with an energy-optimized trajectory to evaluate energy consumption, joint torque, and execution time under identical task conditions. The study demonstrates how energy optimization can reduce total energy use while maintaining task performance.

By bridging the gap between theoretical trajectory planning and realistic simulation, this study provides insights into practical energy-efficient motion planning strategies for industrial robots. The results are expected to contribute to sustainable manufacturing, reduce operational costs, and extend actuator lifetime. Furthermore, the methodology establishes a foundation for future research on multi-objective optimization and adaptive energy-aware control in industrial robotic systems.

Title: Literature Review - Energy-Efficient Trajectory Planning for Industrial Robot Manipulators

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2.1 Trajectory Planning in Industrial Robot Manipulators

Trajectory planning is a fundamental problem in industrial robotics, aiming to generate feasible and smooth joint or Cartesian space motions that allow a robot manipulator to move between desired configurations while satisfying kinematic and dynamic constraints. Traditionally, trajectory planning methods in industrial applications focus on ensuring motion smoothness, positional accuracy, and time efficiency to meet production requirements.

Classical trajectory planning techniques commonly include polynomial-based trajectories, trapezoidal velocity profiles, and spline interpolation methods. Polynomial trajectories are widely used due to their simplicity and ability to ensure continuity in position, velocity, and acceleration. Trapezoidal and S-curve velocity profiles are also popular in industrial controllers, as they limit sudden changes in acceleration and reduce mechanical stress on robot joints.

Trajectory planning can generally be classified into joint-space and Cartesian-space approaches. Joint-space planning is computationally efficient and avoids kinematic singularities, making it suitable for real-time industrial applications. In contrast, Cartesian-space planning provides intuitive path control of the end-effector but often requires inverse kinematics solutions, which may increase computational complexity.

Despite their effectiveness in achieving smooth and time-efficient motion, most conventional trajectory planning methods do not explicitly consider energy consumption as a primary optimization objective. These approaches typically prioritize time minimization or motion smoothness, which can lead to higher actuator torques and increased energy usage. As energy efficiency becomes increasingly important in modern and sustainable manufacturing systems, the limitations of traditional trajectory planning methods highlight the need for energy-aware and optimization-based planning strategies.

2.2 Optimization-Based Trajectory Planning

To overcome the limitations of classical trajectory planning methods, optimization-based approaches have been widely explored in robotic trajectory planning. In these methods, trajectory generation is formulated as an optimization problem, where a cost function is minimized subject to kinematic, dynamic, and actuator constraints. Commonly used objective functions include trajectory smoothness, execution time, joint torque, and dynamic performance indices.

Optimal control techniques play a significant role in optimization-based trajectory planning. Methods such as minimum-time, minimum-jerk, and minimum-torque trajectory optimization have been applied to improve robot motion efficiency. By explicitly incorporating robot dynamics into the optimization process, these approaches can generate trajectories that reduce excessive joint accelerations and actuator loads compared to conventional planning techniques.

Metaheuristic optimization algorithms have also gained considerable attention due to their flexibility in handling nonlinear and multi-objective problems. Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and other evolutionary methods have been employed to optimize robot trajectories by simultaneously considering multiple performance criteria, such as energy consumption, motion smoothness, and task completion time. These methods are particularly attractive for complex robotic systems where analytical solutions are difficult to obtain.

Although optimization-based trajectory planning techniques have demonstrated improved performance over traditional methods, many existing studies rely on simplified dynamic models or indirect energy metrics. As a result, the obtained trajectories may not fully reflect realistic physical interactions, such as friction, contact forces, and actuator nonlinearities. This limitation motivates further research toward integrating realistic dynamics and physics-based evaluation into energy-efficient trajectory optimization frameworks.

2.3 Energy-Efficient Motion Planning for Robot Manipulators

In recent years, energy-efficient motion planning has received increasing attention due to rising energy costs and the demand for sustainable manufacturing systems. Unlike traditional trajectory planning approaches that primarily focus on time efficiency or smoothness, energy-efficient motion planning explicitly considers the reduction of energy consumption during robot motion as a key optimization objective.

Several studies have proposed energy-aware trajectory planning methods by minimizing joint torques, actuator power, or total electrical energy consumption of robot motors. These approaches typically incorporate robot dynamic models to estimate energy usage based on torque, velocity, and acceleration profiles of individual joints. Experimental and simulation results in the literature indicate that energy-optimal trajectories often differ significantly from time-optimal ones, as aggressive accelerations and high-speed motions tend to increase energy consumption.

Multi-objective optimization frameworks have been widely adopted to balance energy consumption with other performance criteria, such as execution time, path smoothness, and positioning accuracy. Techniques such as Genetic Algorithms, Particle Swarm Optimization, and Pareto-based methods have been employed to explore trade-offs between energy efficiency and task performance. These studies demonstrate that significant energy savings can be achieved without substantial degradation in task completion time.

Learning-based approaches have also emerged as promising solutions for energy-efficient motion planning. Reinforcement learning and data-driven optimization methods enable robots to learn energy-efficient motion strategies through repeated interaction with simulated environments. While these methods offer adaptability and flexibility, they often require extensive training data and high-fidelity simulation models to ensure stable and reliable performance.

Despite notable progress, many existing energy-efficient motion planning studies rely on simplified energy models or neglect realistic physical effects such as friction, contact dynamics, and external disturbances. Consequently, the practical applicability of these approaches in real industrial environments remains limited. This gap highlights the importance of integrating energy-efficient trajectory planning with physics-based simulation to achieve more accurate and realistic energy evaluations.

2.4 Physics-Based Simulation in Robotics Research

Physics-based simulation has become an essential tool in modern robotics research, enabling the evaluation and validation of motion planning and control algorithms in a safe and cost-effective manner. Unlike purely kinematic simulations, physics-based simulators model realistic robot dynamics, including inertia, friction, contact forces, and actuator constraints, thereby providing a more accurate representation of real-world robotic behavior.

Simulation platforms such as PyBullet, Gazebo, and MuJoCo are widely used to study robot motion planning and manipulation tasks. These simulators allow researchers to test trajectory planning algorithms under realistic physical conditions, including gravity effects, joint limits, and environmental interactions. As a result, physics-based simulation plays a crucial role in bridging the gap between theoretical algorithm design and practical industrial implementation.

In the context of energy-efficient motion planning, physics-based simulation enables precise estimation of joint torques, power consumption, and total energy usage during task execution. By directly simulating robot dynamics and actuator behavior, these environments facilitate detailed energy analysis that is difficult to achieve using simplified analytical models. Furthermore, simulation-based evaluation allows repeated experimentation under varying conditions without the risk of hardware damage.

Despite these advantages, the integration of physics-based simulation with energy-efficient trajectory planning remains relatively limited in existing literature. Many studies utilize physics engines primarily for validation purposes rather than as an integral component of the trajectory optimization process. This limitation suggests a clear opportunity to develop simulation-driven frameworks that leverage physics-based feedback to generate and evaluate energy-optimal trajectories for industrial robot manipulators.

2.5 Research Gap and Motivation

The reviewed literature demonstrates that significant progress has been made in trajectory planning, optimization-based motion planning, and energy-efficient robot control. Classical trajectory planning techniques are well established in industrial applications and provide smooth and time-efficient motion. Optimization-based approaches further enhance performance by incorporating dynamic constraints and multi-objective criteria, while recent studies have increasingly focused on reducing energy consumption through torque, power, or energy-aware optimization strategies.

However, several limitations remain evident in existing research. Many energy-efficient trajectory planning methods rely on simplified dynamic or analytical models that do not fully capture realistic physical effects such as friction, contact dynamics, actuator nonlinearities, and external disturbances. As a result, the estimated energy consumption may deviate from actual robot behavior in real industrial environments.

Furthermore, physics-based simulation is often used only as a validation tool rather than being tightly integrated into the trajectory planning and optimization process. The potential of physics engines to provide accurate dynamic feedback and realistic energy evaluation during trajectory generation remains underutilized in the current literature. This gap limits the applicability of many existing approaches to real-world industrial robot manipulators.

Motivated by these observations, the present research aims to develop an energy-efficient trajectory planning framework for industrial robot manipulators using physics-based simulation. By integrating realistic dynamic modeling with trajectory optimization, this work seeks to achieve more accurate energy estimation and improved motion efficiency while maintaining task performance. The proposed approach is expected to contribute toward sustainable and energy-aware robotic systems in modern manufacturing environments.