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Trajectory Planning and Optimization Methods for Intelligent Robots

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Abstract. Trajectory planning and trajectory optimization are the key technologies to realize the autonomous operation of intelligent robots. In order to solve the limitations of traditional manual teaching and offline planning in adapting to complex dynamic environments, insufficient movement smoothness and limited adaptability, this paper systematically summarizes the trajectory planning and optimization methods of intelligent robots. On the basis of introducing the intelligent robot trajectory planning framework, this paper compares and analyzes the characteristics and applicable scenarios of two typical smooth trajectory optimization algorithms - Minimum Jerk and Minimum Snap. In addition, this paper summarizes the advantages and disadvantages of the jerk-snap hybrid optimization strategy, and reviews the data-driven trajectory optimization method based on reinforcement learning. Finally, the technical characteristics, existing challenges and future development directions of various methods are summarized and analyzed, which provides reference for the research and engineering application of intelligent robot trajectory planning and optimization technology.

Keywords: intelligent robots, trajectory planning, Minimum Jerk, Minimum Snap, reinforcement learning

1. Introduction

Modern robot systems usually adopt a closed-loop architecture of "perception-planning-execution". The perception module obtains environmental information and the status information of the robot itself through internal and external sensors. The planning module generates the optimal motion trajectory according to the perceived information, and the execution module converts the planned trajectory into the actual movement. The collaborative work of these three modules enables the robot to adapt to its environment.

Among them, intelligent robots put forward strict technical requirements for trajectory planning and optimization under precision operation scenarios. First of all, the trajectory accuracy must reach the submillimeter level to ensure the molding quality and assembly accuracy of the precision operation. Secondly, the smoothness of the movement directly determines the operating stability of the equipment, because the sudden acceleration is easy to cause mechanical vibration, operating deviation and mechanical impact wear. Third, the structural deformation, assembly error and dynamic environmental disturbance during operation require the trajectory to have real-time

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dynamic compensation and adaptive adjustment ability. Traditional manual teaching and offline fixed planning methods cannot meet the needs of these complex working conditions, and it is difficult to achieve high-precision and high-stability intelligent operation. Therefore, intelligent and adaptive trajectory planning and optimization solutions are urgently needed.

This article focuses on the core method of intelligent robot trajectory optimization, and systematically summarizes the technical characteristics, iterative evolution process and integration strategies of two classic trajectory smoothing optimization algorithms - Minimum Jerk and Minimum Snap. In addition, the article also explores the extended application and adaptive optimization ability of these two algorithms in the data-driven framework based on reinforcement learning, which provides clear theoretical support and technical reference for the research and engineering realization of high-precision dynamic trajectory planning technology of intelligent robots.

2. Intelligent robot trajectory planning and optimization framework

2.1. Trajectory planning layer

Intelligent robot trajectory planning is the core technology of autonomous robot operation. At present, this field is gradually developing from the traditional manual programming mode to autonomous planning, multi-sensor integration, virtual and reality simulation verification and online dynamic compensation, so that robots can effectively adapt to the needs of autonomous operation in complex and unstructured dynamic environments. In terms of technical process, the robot first reconstructs the three-dimensional model of the operation scene through 3D vision scanning according to the spatial and geometric constraints of the task, extracts the geometric features of the environment, and generates the initial movement trajectory. Since the initial trajectory only provides the basic spatial trajectory, it is necessary to refine the trajectory through trajectory smoothing, posture adjustment and multi-objective optimization algorithms to improve the smoothness, trajectory feasibility and operational efficiency of the movement.

Before deploying the algorithm, motion feasibility verification must be carried out on the V-REP virtual simulation platform to identify problems such as joint limit overlimit, motion singularity, self-collision and environmental interference [1]. During the simulation process, the status and sensor information of the robot can be collected at the same time to realize the real-time iteration and efficient debugging of the scene, so as to improve the reliability of offline planning. The core modules of the technical framework include three-dimensional visual reconstruction, trajectory posture optimization, virtual collision detection, multi-sensor data fusion, posture positioning based on two-dimensional vision, and real-time visual trajectory tracking. In actual operation, the system relies on vision to quickly determine the initial posture and start the task. By combining visual inspection with real-time tracking and control, the system can perform dynamic trajectory compensation and effectively suppress dynamic disturbances such as workpiece deformation, assembly error and environmental interference, so as to ensure that the autonomous operation of the robot has high precision and high stability.

2.2. Trajectory optimization layer

In the intelligent robot motion planning system, the geometrically feasible trajectory can only meet the basic requirements of obstacle avoidance and target point accessibility. The researchers summarized the current trajectory optimization research characteristics into three aspects: the

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hierarchical integration of front-end trajectory search and back-end trajectory smoothing, the mature application of the low-order Minimum Jerk algorithm in the industrial field, and the continuous iterative optimization of the high-order Minimum Snap algorithm for high-precision vibration suppression applications. In recent years, research has increasingly combined random sampling-based trajectory planning algorithms with trajectory smoothing models to adapt to a variety of operating conditions, such as deformed aircraft and heavy robot arms. The core technical framework mainly focuses on four aspects: trajectory time reallocation, multi-target cost function construction, high-order continuous polynomial interpolation, and dynamic constraint boundary optimization. After obtaining the geometrically feasible trajectory, it is necessary to further optimize its execution efficiency, energy consumption and motion smoothness. Under the strict constraints of joint speed, acceleration and impact, the movement duration of each track segment is redistributed to obtain the optimal trajectory in terms of execution time, energy consumption or smoothness. At present, smooth trajectory generation is mainly based on two classic models: Minimum Jerk and Minimum Snap. Minimum Jerk is optimized by minimizing the square integral of jerk throughout the movement. Its physical significance is clear, because the impact force directly reflects the change rate of motor torque, which is closely related to suppressing mechanical impact and reducing system vibration. In addition, mainstream commercial robot controllers (such as KUKA KRL and FANUC TP) natively support configurable impact parameters, so the threshold for engineering implementation is relatively low. As an advanced high-order optimization method, Minimum Snap further suppresses the residual vibration of the system by minimizing the fourth-order derivative of the position （Snap，the change rate of the torque change rate), and usually shows better vibration suppression performance in highly dynamic motion scenarios. However, the model involves higher-dimensional optimization problems and greater computational complexity, and lacks native support for general-purpose industrial robot controllers, resulting in more restrictions in practical engineering applications.

Table 1. Comparison between Minimum Jerk and Minimum Snap

Comparison Dimension	Minimum Jerk	Minimum Snap
Digital form	quintic polynomial	septic polynomial
Physical Meaning	minimize the torque rate	minimize the variation in the rate of change of torque
Computational complexity	admits an analytical solution	requires QP to solve
Vibration suppression	suppress low-frequency vibrations	suppress low-and mid-frequency vibrations
Real-time performance	Low computational cost and excellent real-time performance	1. High complexity, substantial computational requirements, and poor real-time performance
Application scope	Robotic arm, AGV, low-speed motion platform	Drones and high-precision trajectory planning

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3. Analysis of typical trajectory optimization methods

Robot application scenarios have gradually expanded from a structured environment to a complex dynamic environment, putting forward higher requirements for trajectory continuity, vibration suppression ability and real-time performance. To meet these challenges, researchers have proposed a variety of trajectory optimization methods. Among them, Minimum Jerk and Minimum Snap have received wide attention for their excellent smoothness and clear physical significance.

3.1. Minimum Jerk trajectory optimization method

Minimum Jerk is a mainstream robot trajectory planning optimization theory. By constraining the amount of change and energy of jerk, the method generates an optimal motion trajectory with continuous position, speed and acceleration throughout the movement process, effectively overcoming the defects caused by acceleration mutation in the traditional trajectory, and showing excellent engineering practicality [2]. Compared with the traditional trajectory planning method, the Minimum Jerk trajectory has significant advantages. Its continuous smooth dynamic characteristics effectively inhibit the vibration and mechanical impact caused by movement, thus reducing equipment wear [3]. At the same time, it reduces the servo tracking error and motion over-turning, and improves the positioning accuracy of the robot. In addition, the generated trajectory conforms to the characteristics of natural movement, realizing smooth and flexible movement, which is very suitable for human-computer collaboration. Due to its low computing cost and support for real-time online trajectory planning, this method shows excellent applicability in the overall engineering application.

At present, the Minimum Jerk theory has been widely used in various modern intelligent robot systems, establishing a mature theoretical framework for academic research and engineering applications. In the field of industrial robots, interval analysis is used to optimize the Minimum Jerk algorithm to solve the problem of trajectory smoothness in continuous multi-waypoint motions, making it suitable for sorting and assembly tasks performed by multi-axis industrial robotic arms [4]. Fang Yi and others optimized the Minimum Jerk trajectory of the five-order polynomial by introducing robot kinematic constraints, which effectively inhibited the vibration during the high-speed operation of the parallel grinding robot and improved the quality of precision machining [5]. In the field of warehouse mobile robots, Bianco proposed a time-limited minimum-maximum jerk speed planning algorithm, which optimizes the deceleration curve under vehicle movement constraints to prevent goods from overturning during heavy-duty AGV transportation [6]. Frego and others have developed a double-layer planning framework, while minimizing driving time and jerk, so as to achieve the smooth scheduling and efficient operation of the AGV Group [7]. In the field of human-computer collaboration and special robots, the minimum speed reduction criterion has been combined with obstacle avoidance constraints to realize the safe and smooth movement control of redundant collaborative robotic arms, which is suitable for close-range human-computer collaboration scenarios [8]. In addition, the theory is also applied to the movement planning of rehabilitation robots and intelligent prostheses, which can reproduce the natural movement trajectory of human limbs, reduce compensatory fatigue in the patient's exercise process, and provide key technical support for flexible movement control in medical intelligent robot systems.

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3.2. Minimum Snap trajectory optimization method

Minimum Snap is a high-order extension based on the Minimum Jerk trajectory planning algorithm. By minimizing the fourth-order derivative of the trajectory (Snap), this method maximizes the smoothness of the movement. With the help of higher-order polynomials and Bezier curve modeling, it overcomes the limitations of dynamic parameter discontinuity in the low-order trajectory planning method [9]. Compared with the Minimum Jerk method, this algorithm is optimized with the goal of minimum jerk change and motion smoothing, so as to reduce the instantaneous fluctuation of joint torque and effectively suppress the residual vibration of the terminal actuator under flexible connecting rod and heavy-load operation conditions. Therefore, in the process of high-speed start-stop operation and multi-segment trajectory conversion, the motion oscillation is significantly reduced [10]. Its main advantage lies in its excellent high-order dynamic stability and more effective residual vibration suppression ability, enabling it to meet strict dynamic constraints while capable of carrying out high-precision robot tasks, such as precise positioning and dynamic obstacle avoidance.

At present, Minimum Snap has become the trajectory optimization method of the core of high-precision intelligent robots, and has won the support of a large number of academic research and engineering applications. Mellinger and Kumar were the first to establish the Minimum Snap theoretical framework, laying the technical foundation for high-order smooth trajectory planning. Their methods effectively inhibit vehicle vibration in the process of high-speed operation and rapid attitude conversion, and have been widely used in UAV trajectory planning tasks, such as aerial inspection and high-speed flight [9]. Singh and others adopted the seventh-order Minimum Snap trajectory planning for the tandem industrial robotic arm. The generated trajectory maintains C^4continuity throughout the movement, effectively suppressing the joint impact and residual vibration of the terminal actuator during start-stop operation and point conversion. Compared with the Minimum Jerk trajectory, it reduced end-effector oscillations, improved repeatability in positioning accuracy, prevented workpiece collisions, and enhanced the yield of precision assembly [10]. Gao investigated arc-welding operations in workshop environments densely populated with fixtures and workpiece obstacles, focusing on the machining of spatial curved weld seams for automotive pipes and steel structures. An improved seventh-order Bézier curve was adopted to fit the weld trajectory, while collision detection was achieved using the convex hull property of the Bézier curve, and obstacle avoidance was realized by adjusting the control points. Meanwhile, we optimize the trajectory under the Minimum Snap criterion to realize C^4 continuous motion, reduce welding torch vibration, and enhance weld forming quality. Comparative validation on a six-degree-of-freedom welding robot simulation platform demonstrated that the proposed algorithm simultaneously ensures obstacle avoidance safety, motion smoothness, and continuous welding quality, making it suitable for long-term automated arc-welding tasks in workshop environments with multiple obstacles [11].

4. Intelligent trajectory optimization strategies

4.1. Hybrid Minimum Jerk–Minimum Snap method

In order to improve trajectory smoothness and energy efficiency at the same time, existing studies further combine the optimization criteria of Minimum Jerk and Minimum Snap. Through the weighted coupling strategy, dual-target collaborative optimization is realized, and multi-dimensional physical constraints are introduced in terms of position, speed, acceleration, deceleration and

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instantaneous acceleration, so as to generate a robust trajectory that takes into account smoothness and energy efficiency [12]. This hybrid optimization method achieves a flexible trade-off between suppressing vibration and motion energy consumption through adaptive weight adjustment, which is suitable for the diversified needs of different operating scenarios. In addition, this method has high computing efficiency and strong engineering feasibility. Compared with the optimization method based on a single criterion, the hybrid constraint optimization method overcomes the limitations of excessive energy consumption or insufficient smoothness in the single-target method. However, manual adjustment of weight requires a lot of simulation and on-site experiments, resulting in high parameter tuning costs and limited generalization ability. In practical engineering applications, this hybrid planning method has been widely used in industrial robotic arms and unmanned aerial vehicles (UAV). By applying the weighted Jerk-Snap optimization model to six-axis industrial robots for material handling and loading and unloading operations, dynamic weight distribution can effectively reduce the energy consumption of joint motors, while ensuring that the trajectory is continuous and vibration-free, thus overcoming the high energy consumption problem brought about by the traditional Minimum Snap method and significantly improving stable and economical robot operation for long-term continuous operation. Meng et al. proposed a multi-constrained Jerk-Snap hybrid optimization strategy for hovering and maneuvering flight of loaded drones. This method effectively inhibits the vibration and trajectory shift of the vehicle caused by the crane load, thus improving trajectory tracking accuracy and operation safety during workshop inspection and material transportation [13]. By making up for the limitations of low-order and high-order trajectory optimization methods, such hybrid optimization methods have become a mainstream solution to improve the quality of robot movement and reduce the cost of engineering operation.

4.2. Reinforcement learning-based trajectory optimization method

The traditional Minimum Jerk and Minimum Snap trajectory planning methods rely on precise offline modeling and simulation-based verification, and it is difficult to adapt to the uncertainty in the industrial environment, such as thermal deformation, assembly tolerance and environmental disturbance caused by welding. The data-driven planning and control method based on reinforcement learning realizes adaptive optimization of the trajectory through real-time interaction with the environment, which effectively makes up for the shortcomings of the traditional modeling method in terms of adaptability [14]. The method constructs a continuous state-action decision-making model, takes the posture, visual perception and process parameters of the robot as state input, and optimizes the trajectory through hierarchical strategies. The high-level strategy works together with the traditional trajectory smoothing framework to ensure the continuity of the overall trajectory; while the low-level strategy precisely adjusts the joint output to achieve dynamic error compensation. In addition, a reward shaping mechanism can transform sparse task feedback into evaluation signals based on continuous gradients, thus improving learning efficiency and trajectory optimization quality. Therefore, this method can optimize motion smoothness, tracking accuracy and process quality at the same time, which is especially suitable for complex nonlinear dynamic welding scenarios. In practical industrial applications, this technology has been successfully applied to a variety of robot welding tasks. Hu et al. applied deep reinforcement learning to the obstacle avoidance trajectory planning of welding robots in narrow spaces, which effectively solved the problem that the traditional fixed trajectory could not adapt to the geometric changes of the workpiece, and significantly improved the welding stability and trajectory success rate under complex operating conditions [14]. He et al. proposed an adaptive trajectory compensation strategy based on reinforcement learning, which is used for body surface welding, which can compensate for

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the trajectory deviation caused by thermal deformation caused by welding in real time, and significantly improve the accuracy and welding consistency of welding points [15]. In addition, the optimization framework that combines digital twins and reinforcement learning can iteratively optimize welding trajectory parameters through virtual and physical joint training, effectively reduce on-site debugging costs, and improve the robustness and production adaptability of robot welding systems on large structural components [16].

5. Conclusion

Trajectory planning and optimization play a key role in the architecture of intelligent robot systems. They are not only the core units of perceptual information processing, but also the key decision-making link for robot movement execution. Although the technology of intelligent robot trajectory planning and optimization has become more and more mature, there is still a gap between the ideal simulation model and the real operating environment. In complex scenarios such as human-computer collaboration or operation in a dynamic environment, factors such as structural deformation, environmental changes and human interference may easily lead to the failure of the preset offline trajectory, and it is difficult for traditional optimization algorithms to quickly respond to real-time changes in operating conditions. Although the adaptive planning method based on reinforcement learning has the advantages of dynamic closed-loop control, it has not yet achieved large-scale engineering applications and still relies on a large amount of training data to ensure operational stability. At the same time, robot motion planning must take into account trajectory smoothness, operational efficiency and safety at the same time. Because these goals are inherently contradictory, most of the existing methods rely on manual parameter tuning and lack automated and intelligent dynamic trade-off optimization mechanisms. In the future, intelligent robots are expected to realize real-time perception of the environment and autonomous dynamic trajectory adjustment with the help of high-order trajectory optimization and intelligent learning algorithms, thus reducing dependence on preset programs and manual teaching. The deep integration of multi-sensor information fusion, high-precision force control and adaptive compensation technology will further improve motion accuracy and anti-interference ability, and achieve global optimization of operation quality, execution efficiency and energy consumption. With the continuous maturity of human-computer collaboration and multi-robot collaboration technology, intelligent robots will overcome the limitations of fixed workstation operation, flexibly adapt to complex production line environments, complete high-precision and complex tasks, and promote the evolution of the robot system to an integrated perception-planning-execution framework with end-to-end intelligence, providing key technical support for the digital transformation of high-end intelligent manufacturing.

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