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A review of the trajectory planning of Industrial robots

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Abstract. With the continuous extension of the application scenarios of industrial robots, industrial robots have made great contributions to increase productivity and automation in the industrial field. And trajectory planning of industrial robots is the key link for its successful completion of tasks. In order to deeply analyze the mechanism of trajectory planning of industrial robots, this paper firstly introduces the principle of trajectory optimization. And then it reviews the relevant theories and methods of trajectory planning. Finally, it summarizes the development trend of trajectory planning of industrial robots.

Keywords: Industrial Robots; Trajectory Planning; Industrial Field Application Scenarios.

1. Introduction

In the midst of the fourth Industrial Revolution, the global intelligent manufacturing industry has developed at a high speed.And in the process of intelligent transformation in the industrial field, there are increasing demands on labor productivity, safety and burden of manual work. Industrial robots which have the feather of high precision, high efficiency and high flexibility have received extensive attention from the industrial and scientific research communities in this process. In the industrial world, articulated industrial robots have the widest range of applications, such as welding, painting, handling, assembly, machining and other fields. And for scientific research, researchers study industrial robots from the direction of kinematics, dynamics, and motion control systems. And as the supporting technology of robot motion control,the trajectory planning of industrial robots is the key point affecting efficiency, smoothness and energy consumption. So in the field of robotics,the trajectory planning has become an important research topic.

2. Principles of trajectory planning

2.1 The Classification of The Trajectory Planning

Trajectory refers to the distance traveled by the end effector, which finally outputs time series of position, velocity, and acceleration. The trajectory planning is to generate the motion trajectory of industrial robots by using curve fitting method in the corresponding space(Cartesian space or joint space) based on the kinematic analysis . In essence, trajectory planning is a strategy. Based on path planning, this strategy aims to achieve precise control of industrial robots with certain motion efficiency and precision.Therefore,the trajectory planning process does not involve artificial intelligence.And in the planning of the robot, it belongs to the underlying planning. From the aspects of space,the trajectory planning can be divided into Cartesian space and joint space trajectory planning.(as shown in Table I)

Table 1. Classification and comparison of trajectory planning

Trajectory planning methods	principle	advantages	drawbacks
Trajectory planning in Cartesian space	Direct planning of motion trajectories in the Cartesian space where the robot end-effector is located.	Intuitive and easy to understand	After planning, a lot of calculations are still needed to drive the joints, which is computationally intensive and impractical.
Trajectory planning in Joint space	Different curves were used to interpolate the joint displacement, and the time series of each joint Angle was obtained while the robot passed through all the path points, and the joint space trajectory planning was completed	Low computational effort, high efficiency, no singularity problem	It is necessary to balance efficiency and trajectory smoothness

2.2 The Process of Trajectory Planning

Specifically, after path planning, the path points are transformed into the angle values of joints by the inverse kinematics solution method.Then, the trajectory planning officially begins.In this process, the time series of joint angles of industrial robots are obtained by different trajectory planning methods. It is important to note that in each period of trajectory,the time of each joint movement must be consistent.This temporal consistency makes sure that all the joints can reach the specified path point at the same time. In addition, the velocity, acceleration and jerk of each joint are the constraints of interpolation operation at each path point. Joint space trajectory planning must consider these constraints and meet the requirements of joint displacement, attitude continuity and motion parameters within the allowable range,which must be considered in trajectory planning in the joint space (as shown in Fig. 1).

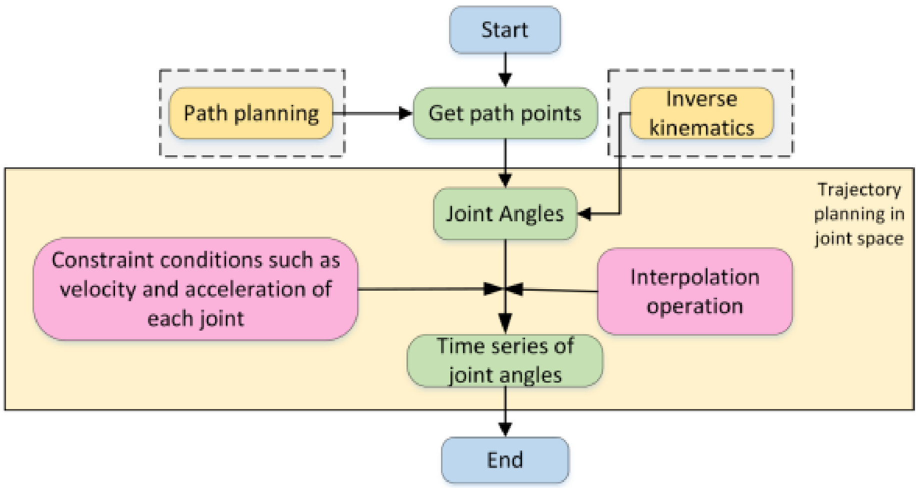

Fig. 1 The specific steps of trajectory planning in joint space

3. The trajectory planning algorithms

There are many methods for trajectory planning, and everyone has its own characteristics. Recently, the trajectory planning methods in joint space are the most used methods. They belong to the general trajectory planning, which mainly start from the geometric characteristics of the trajectory.The most used trajectory planning methods in joint space are polynomial interpolation, spline curve interpolation (B-spline curve, non-uniform B-spline curve) and so on.[1]

Among these methods, polynomial and B-spline interpolation methods are the most used ones. The polynomial trajectory planning method refers to the realization of industrial robot trajectory planning with a polynomial function as the fitting function. With the research, it can be found that the higher the polynomial order, the higher the trajectory planning accuracy, but the amount of computation will also increase. In practice, in order to reduce the amount of computation, 3rd order polynomials are generally used for trajectory planning in joint space. The 3rd order polynomial interpolation method interpolates trajectories with polynomials containing 4 parameters, which is widely used in the industrial field due to its ability to effectively control the robot end-effector. Meanwhile, small amount of computation, as well as the good continuity of position and velocity. [2] [3] [4] However, since the 3rd polynomial interpolation does not guarantee continuous acceleration, it may result in a large shock to the robot. Therefore, many scholars use high-order polynomials and mixed polynomials to realize trajectory planning of industrial robots, and obtain trajectories with high precision, good smoothness and stability. [5] [6] [7] [8].

In view of the accuracy and computational complexity of polynomial trajectory planning, spline curve has been widely concerned by researchers for the curve smoothness and transition points. Among them, B-spline curve who overcomes the disadvantages of Bessel curve, such as poor local modification and weak control ability, is widely used in all kinds of engineering. However, due to the complexity of the calculation process of B-spline curve, the order of B-spline function is generally lower than 3 times in engineering applications. Specifically, the trajectory planning based on B-spline is to obtain the time series of each joint angle by the inverse calculation method of B-spline function.At the same time, scholars have implemented trajectory planning by using B-spline algorithms of different orders, which not only improves the computational efficiency but also solves the Runge phenomenon problem of polynomials. [9] [10] [11] [12] However, it is not true that the higher the order of the spline curve, the better the trajectory planning effect.Gasparetto analyzed the interpolation effect of different orders B-spline curve under the same conditions, and concluded that there were some differences in the effect of different-orders B-spline curve under different requirements.[13] Therefore, for the amount of computation, many scholars use intelligent algorithms to solve the optimal trajectory of industrial robots [14] [15] [16]. Meanwhile, Optimal trajectory planning is another research direction in the field of robotics. Many scholars carry out research in the aspects of time optimal, capability optimal, impact optimal and multi-objective optimal trajectory planning, and propose a variety of intelligent algorithms to realize the optimization process of optimal trajectory planning. [17] [18] [19] [20] [21] [22] [23]

In summary, curve interpolation is one of the most important aspects in the process of trajectory planning. However, no matter how to interpolate the trajectory of industrial robots, the principle is similar, and the curve is used to fit the trajectory. In terms of curve selection, there are some differences in the performance of different curves for different requirements such as accuracy and speed. In this process, the calculation amount and fitting accuracy are the most important evaluation criteria. In terms of optimal trajectory planning, how to comprehensively consider the factors such as robot efficiency, energy consumption, wear, running smoothness, optimal torque and optimal distance, and realize the research of high-precision, high-efficiency and intelligent universal trajectory planning algorithm is the future development direction of robot trajectory planning.

4. Trends in industrial robot trajectory planning

Based on the above research on the principle and related technologies of trajectory planning for industrial robots, this paper will put forward the development trend of trajectory planning from two aspects of curve interpolation method and optimal trajectory planning.

4.1 A Demand-based Interpolation Method for Trajectory Planning

Compared with the mature polynomial interpolation methods, B-spline curve and non-uniform rational B-spline curve can better meet the requirements of computational pressure and accuracy. However, the solution process of the high-order B-spline curves is also very complicated. In addition, the improvement of the order of the curve does not necessarily mean that it can meet the corresponding industrial requirements (such as the maximum value of velocity, acceleration and the smoothness of the curve). Therefore, the selection of demand-based curve interpolation methods is a trend in its development.

4.2 Multi-objective trajectory planning of industrial robots

With the differences in application scenarios of industrial robots, industrial robots have different requirements for their operation time, energy consumption and jerk. In addition, in many scenarios, the distance and torque of industrial robots also need to be further constrained. Therefore, the multi-objective trajectory planning is the development trend of optimal trajectory planning of industrial robots.

4.3 Intelligent, Modular and Integrated Motion Planning for Industrial Robots

Industrial robot motion planning includes path planning and trajectory planning. The modularization, integration and intelligent development of industrial robot motion planning is not only an important part of the intelligent development of industrial robots, but also an important guarantee for the efficient operation of industrial robots. The integrated development of Cartesian space path planning and joint space trajectory planning is an important development trend of industrial robot motion planning.

5. Conclusion

Firstly,this paper introduces the principle of industrial robot trajectory planning.Then it briefly introduces the algorithm of trajectory planning of industrial robots.Finally it summarizes the development trend of trajectory planning of industrial robots,which will provide a new idea for the intelligent development of industrial robot motion planning.

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