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Minimum time path planning of robotic manipulator in drilling/spot welding tasks

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Abstract

In this paper, a minimum time path planning strategy is proposed for multi points manufacturing problems in drilling/spot welding tasks. By optimizing the travelling schedule of the set points and the detailed transfer path between points, the minimum time manufacturing task is realized under fully utilizing the dynamic performance of robotic manipulator. According to the start-stop movement in drilling/spot welding task, the path planning problem can be converted into a traveling salesman problem (TSP) and a series of point to point minimum time transfer path planning problems. Cubic Hermite interpolation polynomial is used to parameterize the transfer path and then the path parameters are optimized to obtain minimum point to point transfer time. A new TSP with minimum time index is constructed by using point-point transfer time as the TSP parameter. The classical genetic algorithm (GA) is applied to obtain the optimal travelling schedule. Several minimum time drilling tasks of a 3-DOF robotic manipulator are used as examples to demonstrate the effectiveness of the proposed approach.

Keywords: Minimum time; Mixed integer; Path planning; Point to point motion; Drilling/ spot welding task

1. Introduction

Minimum time motion planning problems for robotic manipulator were widely studied in industrial applications and several efficient solution methods are proposed. Aiming at the minimum time motion planning problem along given path, Bobrow et al. [1] proposed a phase plane analysis approach to obtaining minimum time motion trajectory with confined torque. The similar problems were solved by Zhang et al. [2] with a greedy search algorithm and Zhang et al. [3,4] with convex optimization approaches. For the more general minimum time point-to-point motion planning problem, the solution becomes complex since the path and the motion along the path need to be optimized simultaneously. Bobrow [5] applied the phase plane analysis approach to calculate minimum motion time along given path, then the point-to-point motion planning problem was solved by searching minimum time path in feasible path space.

Different from the simplex motion planning problems as mentioned above, in manufacturing industry there exists a class of complex tasks called multi-points manufacturing, such as drilling [6,7], spot welding and assembly [8]. These tasks have many unordered points and hence it is necessary to plan an optimal strategy to traverse all the desired points in an orderly way while satisfying the requirement of minimum distance, minimum time or minimum energy, etc.

It is shown that the studied drilling/ spot welding tasks can be described by a performance limited traveling salesman problem (TSP) [9–11]: the manipulator effector acts as the salesman, it starts from one machining point and passes through each point just by once meanwhile it must be full stopped to finish the machining task. Since its high computational complexity, the solution of TSP is always an open problem. Currently, the feasible solutions of TSP can be classified by enumeration method, dynamic programming, branch and bound method, or intelligent optimization method

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(such as genetic algorithm (GA) [12], simulated annealing (SA), Particle Swarm Optimization (PSO), etc).

In order to simplify the problem, the common path planning strategies for multi points manufacturing assume the transfer path between any two points is straight line, and the problem can be described as a TSP with minimum distance index [11]. However according to Bobrow [8] and Dubowsky and Blubaugh [9], it is shown that due to the nonlinear expressions of the manipulator kinodynamics and gravitational torques, it is non-equivalent between the minimum time path and the minimum distance path, even the minimum time path from point i to point j is also different from the point j to point i path. Hence besides the optimization of travelling schedule of the set points, the transfer paths between machining points also need to be optimized to obtain the minimum transfer time.

In this paper, the minimum time path planning problem for multi points manufacturing is studied. Since the travel schedule of the set points and the detailed transfer path between points must be optimized simultaneously, a mixed integer optimal control formulation is constructed to describe the problem. Based on the start-stop movement in drilling/spot welding task, the problem can be further converted into a pure integer linear programming problem and a series of point to point minimum time transfer path planning problems. In this paper, a typical genetic algorithm (GA) is applied to solve the generated integer linear programming problem. And cubic Hermite interpolation polynomial is used to parameterize the transfer path and then the path parameters are optimized to obtain minimum point to point transfer time.

2. Problem description

In practical applications, the 6-DOF robotic manipulator is usually required to obtain the free position and orientation output of the end effector. The common configuration of a 6-DOF manipulator is that the first three joints are used to locate the position of the end effector and the last three joints realize the orientation adjustment through cooperation.

In this paper, we focus on the position optimization at each time and the effector orientation can be calculated automatically according to the manufacturing requirement. Hence, only the first three joints of manipulator are discussed here. The dynamics model of robotic manipulator with first three joints can be formulated

$$\tau = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \dot{\mathbf{q}}^{\mathrm{T}}\mathbf{C}(\mathbf{q})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}), \tag{1}$$

where $\mathbf{q} \in \mathbf{R}^n$ denotes the vector of joint angular position, $\boldsymbol{\tau} \in \mathbf{R}^n$ denotes the vector of joint toques, $\mathbf{M}(\mathbf{q}) \in \mathbf{R}^{n\times n}$ is the inertia matrix of manipulator which is symmetric in which the diagonal elements $\mathbf{M}(j,j)$ describe the inertia seen by joint j and the off-diagonal elements $\mathbf{M}(i,j)$ represent coupling of acceleration from joint j to the generalized force on joint i, $\mathbf{C}(\mathbf{q}) \in \mathbf{R}^{n\times n\times n}$ contains the information of centrifugal and Coriolis forces in which the centripetal torques are proportional to $\dot{\mathbf{q}}^2(i)$, while the Coriolis torques are proportional to $\dot{\mathbf{q}}(i)\dot{\mathbf{q}}(j)$, $\mathbf{G}(\mathbf{q}) \in \mathbf{R}^n$ is the vector of gravity-induced torques which always exists even when the robot is stationary or moving slowly, $n = 3$.

The goal of this paper is to plan a reasonable path along which the manipulator drills all the given points only by once while the task time is minimum under the dynamics limits of the manipulator.

Let n_c denote the number of the task points. Define $\mathbf{p}_1, \mathbf{p}_2, \cdots, \mathbf{p}_{n_c}$ as the effector positions in task space corresponding to the n_c drilling points and $\mathbf{p}_i \in \mathbf{R}^3$. The motion performance of each joint is restricted by the torque constraint,

$$-\boldsymbol{\tau}_{\mathrm{B}} \le \boldsymbol{\tau} \le \boldsymbol{\tau}_{\mathrm{B}}. \tag{2}$$

And the joint velocity constraint,

$$-\dot{\mathbf{q}}_{\mathrm{B}} \le \dot{\mathbf{q}} \le \dot{\mathbf{q}}_{\mathrm{B}}, \tag{3}$$

where the joint velocity satisfies $\dot{\mathbf{p}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}$ and $\mathbf{J}(\mathbf{q})$ denotes the Jacobian matrix of the forward kinematics map.

Since the end effector need keep still during the drilling/spot welding process, then we have $\dot{\mathbf{q}}_i = 0$ corresponding to the ith point position $\mathbf{p}_i$ in task space with $i = 1, 2, \cdots, n_c$. Above all, the desired minimum time path planning problem for drilling/ spot welding tasks has the following formulation.

$$\min_{\mathbf{q}(t)} \quad T_{\mathrm{f}}$$
$$\text{s.t.} \begin{cases} \mathbf{q}_i - \mathbf{Q}\mathbf{W}_i = 0, \\ \dot{\mathbf{q}}_i = 0, i = 1, 2, \cdots, n_c, \\ \sum_{i=1}^{n_c} \mathbf{W}_i = [1, 1, \cdots, 1]_{n_c}^{\mathrm{T}}, \\ \boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}), \\ -\boldsymbol{\tau}_{\mathrm{B}} \le \boldsymbol{\tau} \le \boldsymbol{\tau}_{\mathrm{B}}, -\dot{\mathbf{q}}_{\mathrm{B}} \le \dot{\mathbf{q}} \le \dot{\mathbf{q}}_{\mathrm{B}}, \\ \mathbf{q} \in \Omega_q. \end{cases} \tag{4}$$

where, $\mathbf{Q} = \left[\mathbf{q}_1, \mathbf{q}_2, \cdots, \mathbf{q}_{n_c}\right]_{n\times n_c}$ contains all the joint positions of task points, and $\dot{\mathbf{q}}_i$ denotes the joint velocity at the ith task position, $\mathbf{W} \in \mathbf{Z}^{n_c\times n_c}$ act as a enable switch to ensure the manipulator pass all the given points only by once, $\mathbf{W}_i \in \{0,1\}^{n_c}$ is a n_c-dimension column vector, $\Omega_q$denotes the geometry constraint of the joint position, $0 = t_1 < t_2 < \cdots < t_{n_c} = T_{\mathrm{f}}$.

Problem (4) is a typical mixed integer optimal control problem. Similar to Dubowsky and Blubaugh [9], since the motion velocity of each joint need drop to zero at the task point, Problem (4) can actually be decomposed into a minimum time TSP and a series of point to point minimum time path planning sub problem with only continuous variables.

In this paper, each point to point path planning subproblem is solved by a direct parameterization approach to obtain minimum transfer time T_{ij}, then minimum time TSP is constructed and solved by a typical genetic algorithm (GA).