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Research paper

Optimal time-jerk trajectory planning for industrial robots

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ABSTRACT

A methodology for time-jerk synthetic optimal trajectory planning of robotic manipulators is described in this paper. The trajectory is interpolated in the joint space by means of 5th-order B-spline and then optimized by the elitist non-dominated sorting genetic algorithm (NSGA-II) for two objectives, namely, traveling time and mean jerk along the whole trajectory. 5th-order B-spline interpolation technique enables the trajectory to be constrained in the kinematic limits of velocity, acceleration, and jerk while satisfying the continuity of jerk. NSGA-II as a multi-objective optimization technique is used to address the time-jerk optimal trajectory planning problem. The obtained Pareto optimal front provides decision-makers flexible selections on non-dominated solutions for industrial applications. Two performance measures are presented to evaluate the strength of the Pareto optimal front and to select the best optimal solution respectively. Simulations and experiments validate the effectiveness and practicability of the proposed methodology in comparison with those provided by another important trajectory planning methodology.

1. Introduction

Robot manipulators are nowadays widely used in industrial assembly lines and manufacturing systems. In industrial robotic applications, the trajectory planning problem has been a hot spot. Voluminous studies have been conducted to address the trajectory planning for the optimization on minimum time, minimum energy, and minimum jerk. Hybrid optimization approaches featuring expected multi-faceted performance of the trajectory execution have been arousing increasing interest.

The trajectory planning is generally carried out in the operating space and in the joint space. In the operating space, the trajectory of the end-effectors can be naturally described. However, such trajectory planning would easily lead to kinematic singularities and manipulator redundancy. The joint space-oriented methods guarantee the smoothness of each joint movement with an expense of position accuracy reduction in the operating space. As Gasparetto pointed out in Ref. [1], the trajectories were planned in the joint space in most cases.

In the joint space, trajectories have been mostly constructed by several interpolation functions such as polynomial, spline, Bezier, and NURBS, etc. Conventional interpolation functions include the “343” approach developed by Cook and Ho [2] and the “445” approach presented by Petrinec and Kovacic [3]. Recently, a novel “5455” method was proposed by Boscariol et al. [4]. The methods are based on a composition of polynomial functions of different orders. Splines functions have been used as trajectory primitives to ensure acceleration continuity or jerk continuity. Xu et al. [5] applied Bezier curve to fitting the joint trajectory. The main drawback of Bezier curve lies in the fact that the change of one internal knot would affect the

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entire trajectory thereby making the trajectory re-computed. B-splines are distinguished by its good local support property. Various types of B-spline have been used to construct the joint trajectories especially for the aim of satisfactory trajectory smoothness. Ramabalan et al. [6] adopted uniform cubic B-spline for optimal trajectory interpolation where joint jerks were restricted with limiting values. To further realize the jerk continuity, Gasparetto and Zanotto [7] suggested quintic B-spline in the joint trajectory interpolation and optimized the trajectory with sequential quadratic programming (SQP). In 2010, Zhu et al. [8] used 7th-order B-spline for trajectory interpolation and obtained a time-optimal trajectory using SQP method.

In order to improve the manufacturing productivity and the movement stability, trajectories with short execution time or smooth profile are highly desired. Many time-optimal techniques have been investigated in the past decades, such as dynamic programming techniques [9] and phase plane methods [10]. Recently, Rubio et al. [11] proposed a straightforward method to obtain the minimum time trajectory involving obstacles, in which no pre-assumptions are set for the path. Xiao et al. [12] by using the cubic polynomial fitting method converted the path of Cartesian space and constraints of joint space into parameter space, and obtained a smooth and time-optimal trajectory for online applications. Taking into account of the effects of viscous friction, the time-optimal optimization problem becomes non-convex. As for that, Reynoso-mora et al. [13] presented a discretization scheme to relax the referred non-convex formulations. Moreover, Abu-Dakka et al. [14] developed a new genetic algorithm methodology for time-optimal and collision-free trajectory in complex environments. Apart from the traveling time optimization, minimization of the jerk is of significance to the performance of manipulator. Kiriakopoulos and Saridis [15] earlier noted that trajectory with minimum jerk performed better tracking capability. It was suggested as an alternative method to bound the variation rates of the joint torques [16]. As Gasparetto pointed out in Ref. [1], the jerk minimization is able to achieve reduced tracking error, smaller excitation of resonance frequencies, and suppressed stresses induced to the actuators. Integral of the squared jerk was taken as the optimized objective function for jerk optimization in the studies [7,16–18]. Accordingly, spline was applied to interpolate the trajectory via-points [7,16–18].

In the manufacturing process with industrial manipulators, motion movements are usually required to be executed in a time-jerk optimal manner. Time-jerk optimal trajectory planning schemes have been proposed in the scientific literature [7,16–19]. Gasparetto and Zanotto adopted an objective function composed of two terms:one term is proportional to the total execution time and the other is proportional to the integral of the squared jerk [7,16]. Furthermore, two minimum time-jerk trajectory planning methods were evaluated and experimentally validated in the Cartesian space [18]. The simulation and experimental results substantiated the effectiveness of the techniques. However, the two weights of the objective function still require artificial adjustment and thus the method is not so applicable.

A conventional route applied by researchers is to convert all objectives into a single objective function. Nowadays, an emerging alternative is to employ multi-objective evolutionary algorithms to solve the problems. In Ref. [20], a constrained multi-objective PSO algorithm was applied to the joint trajectory optimization in order to minimize the traveling time, the energy and the distance of the end-effector. In Ref. [21], the multi-objective genetic algorithm (MOGA) was utilized to minimize the traveling time and the disturbance to the space manipulator base. Saravanan et al. [22,23] studied two evolutionary algorithms (namely, multi-objective differential evolution (MODE) algorithm and NSGA-II) in tackling with trajectory optimization problems. The simulation results indicated that MODE technique converged quickly than NSGA-II algorithm while NSGA-II algorithm performed better to provide more non-dominated solutions. Shi et al. [24] proposed to apply quintic non-uniform rational B-spline (NURBS) to construct curves for manipulator trajectory planning with respect to multi-objective (time optimal, energy optimal and smoothness optimal). Comparing with 5th order B-spline, quintic NURBS makes the trajectory more flexible and easier to be modified but also requires more complicated mathematical modelling because its mathematical forms involve n weights to be calculated. In terms of multi-objective optimization, NSGA-II was also adopted to optimize the trajectory. Shi et al. [24] carried out the simulations rather than experiments to validate the multi-objective optimal trajectory planning technique.

This study reports a multi-objective technique to obtain time-jerk optimal trajectories of robot manipulators. With respect to most time-jerk optimization techniques in past scientific literature as known to date, NSGA-II, a high-performance multi-objective algorithm, is adopted to deal with time-jerk trajectory optimization problem with nonlinear constraints.

This paper is organized as follows. In Section 2, the trajectory optimization problem is stated; Quintin B-spline is chosen to construct the joint trajectory. In Section 3, NSGA-II is applied to optimize the multi-objective functions for the trajectory. In Section 4, two performance measures for the Pareto front are delineated in detail. In Section 5, the simulation and experimental results are presented with relevant discussion. Finally, Section 6 outlines the main conclusions.

2. Problem statement

2.1. Formulation of the optimization problem

The industrial manipulator PUMA560 with six degrees of freedom is considered in the problem. In industrial applications, manipulators are always required to move through a sequence of via-points in the operating space. However, it is relatively difficult to directly execute the trajectory planning in the task space. The position and orientation of the end effector are not easy to be measured in real time to provide feedback for the robot controller. It requires complicated mathematic modeling and heavy computation to take the dynamic constraint (for instance, torque) and kinematic constraints (usually velocity and acceleration) into account in the Cartesian space. Trajectory planning is thus in most cases carried out in the joint space. The above consecutive via-points in the operating space are transformed to a sequence of knot points in the joint space through