



Research paper

An approach for smooth trajectory planning of high-speed pick-and-place parallel robots using quintic B-splines

Yuhang Li^a, Tian Huang^{a,b,*}, Derek G. Chetwynd^b^a Key Laboratory of Mechanism Theory and Equipment Design of State Ministry of Education, Tianjin University, Tianjin 300072, China^b School of Engineering, The University of Warwick, Coventry CV4 7AL, UK

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ABSTRACT

This paper presents a new, highly effective approach for optimal smooth trajectory planning of high-speed pick-and-place parallel robots. The pick-and-place path is decomposed into two orthogonal coordinate axes in the Cartesian space and quintic B-spline curves are used to generate the motion profile along each axis for achieving C^4 -continuity. By using symmetrical properties of the geometric path defined, the proposed motion profile becomes essentially dominated by two key factors, representing the ratios of the time intervals for the end-effector to move from the initial point to the adjacent virtual and/or the via-points on the path. These two factors can then be determined by maximizing a weighted sum of two normalized single-objective functions and expressed by curve fitting as functions of the width/height ratio of the pick-and-place path, so allowing them to be stored in a look-up table to enable real-time implementation. Experimental results on a 4-DOF SCARA type parallel robot show that the residual vibration of the end-effector can be substantially reduced thanks to the very continuous and smooth joint torques obtained.

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1. Introduction

Recent years have seen ever increasing demands from food, pharmaceutical, packaging and many other light industries for high-speed pick-and-place parallel robots using limbs containing proximal revolute actuated joints and parallelograms. This is exemplified by the many very successful applications of Delta robots and similar types [1–5]. From a system viewpoint, the capability and efficiency of high-speed pick-and-place parallel robots clearly depends on desirable dynamic characteristics and good quality computer control, but also requires sound trajectory planning for achieving superior performance in terms of smoother joint torques, lower residual vibrations and shorter cycle times [6–9]. Large amounts of effort have been devoted to trajectory planning of pick-and-place operations over the last few decades. The currently available approaches can be broadly classified into two categories: path-based trajectory planning and coordinate-based trajectory planning.

Path-based trajectory planning is concerned with first generating an appropriate geometric path parameterized with respect to the arc length and then designing a proper motion profile along that path. For example, Gauthier et al. [10] took Lamé curves with G^2 -continuity at square corners linking the vertical and horizontal segments, and employed a '4-5-6-7 polynomial' with C^3 -continuity as the motion profile. The trajectory was then generated by minimizing the root-mean-square value of the time-derivative of the kinetic energy per unit mass of the payload. However, although the Lamé curve

* Corresponding author at: Tianjin University, 92 Weijin Road, Nankai District, Tianjin, China School of Mechanical Engineering, Tianjin 300072, China.
E-mail address: tianhuang@tju.edu.cn (T. Huang).

parameters can be optimized off-line, the point coordinates of the curve cannot be expressed explicitly in terms of the arc length. Therefore, a nonlinear algebraic equation has to be solved in the on-line coarse interpolation to determine the point coordinates associated with an interpolated arc length. In order to reduce the computational burdens in real time implementation, Masey et al. [11] suggested taking a bisected ellipse as the geometric path such that the arc length along the path could be approximated as a linear function of two normalized parameters so as to include any specified durations of constant velocity or degree of asymmetry. They concluded that the use of an asymmetry factor would be helpful to reduce peak joint torques. The transition linking the vertical and horizontal segments could also be shaped as a Bézier curve, clothoid spline or quintic polynomial for achieving at least G^2 -continuity [12–16].

Compared to path-based trajectory planning, it can be easier to use coordinate-based trajectory planning in either the Cartesian or the joint space. Planning in the joint space involves first transforming the coordinates of a set of via-points on a geometric path into a sequence of joint displacements *via* inverse kinematics, and then generating the motion profiles for each joint by interpolation subject to a set of specific constraints provided by the design requirements [17–21]. For example, Gosselin and Hadj-Messaoud [18] employed a ninth-order polynomial for a single motion profile to guarantee C^3 -continuity by inserting a lift-off and a set-down point. They concluded that undesirable joint torque fluctuations arising from the use of higher order polynomials could be improved by adjusting the time intervals when the lift-off and set-down points are reached or by using a combination of a number of piecewise lower order polynomials. There are many other well-developed piecewise motion profiles available for this purpose, achieving at most C^3 -continuity throughout the entire trajectory, for instance 3–4–5 polynomial, 4–5–6–7 polynomial, modified sine, modified trapezoid, and many others [6].

In order to achieve C^4 -continuity for a smooth motion profile throughout the entire trajectory, there can be potential advantages in using a fifth-order B-spline as the interpolation function. The trajectory planning problem can then be stated as the determination of the sequence of time intervals necessary for a spline to connect two adjacent knots by minimizing a weighted performance index subject to a set of specific constraints. In this context, Constantinescu and Croft [22] proposed a method for minimum time trajectory planning subject to the limits imposed upon the joint torques and their first derivatives. Gasparetto et al. [23–25] presented an algorithm for optimal smooth trajectory planning by minimizing, subject to limits on joint velocity, acceleration and jerk, a weighted sum of the integral of joint jerk squared and the total cycle time. Similarly, trajectory planning in the Cartesian space involves first generating motion profiles along two orthogonal axes of a path lying in a plane and passing through a set of via-points, and then transforming the interpolated point coordinates into the corresponding joint variables *via* inverse kinematics [26–29]. Optimization problems can be formulated in the Cartesian space similar to those in the joint space.

With the B-spline interpolation ensuring C^4 -continuity, an obvious advantage of optimal trajectory planning in the joint space is that it should be easier to impose a set of specified limits upon the actuated joints. However, a problem encountered in practice is that the optimized motion profiles are configuration dependent; it is difficult, if not impossible, to solve the resulting complicated nonlinear programming problems online. Note that a smooth motion profile planned in the Cartesian space ensures that in the joint space at nonsingular configurations, and the joint torques are closely related to the joint accelerations. Therefore, the development of a widely-effective, architecture and configuration free approach to generate the smooth motion profiles in the Cartesian space would be highly beneficial for real-time implementation.

Responding to the many practical needs and inspired by the method proposed in [23], this paper presents a new approach for smooth trajectory planning of high-speed pick-and-place parallel robots using quintic B-splines. The method features an initial offline determination of two key factors dominating the normalized motion profiles along a path defined in a local frame of the Cartesian space, followed by the online generation of the smooth joint trajectories using a look-up table. The remainder of this paper is organized as follows. Section 2 defines a pick-and-place path in a local frame, employs fifth-order B-splines to generate the motion profile along each axis of the path with C^4 -continuity, and so identifies two non-dimensional control factors. In Section 3, the influence of these two factors on the maximum acceleration and jerk over the path is investigated, leading to an optimization problem by maximizing a weighted performance index. This allows the relationship between the two factors and the width/height ratio of the path to be established offline by curve fitting, which, in turn, enables ready online generation of the smooth joint trajectory for real-time implementation. Section 4 presents results from both simulations and experiments using a 4-DOF SCARA type parallel robot [5] to demonstrate the good performance of the proposed approach for achieving smooth joint torques and thereby reducing residual vibrations of the end-effector. Conclusions are drawn in Section 5.

2. Generation of geometric path and motion profile in the Cartesian space

2.1. Description of the geometric path

As shown in Fig. 1, let $P_i(x_i, y_i, z_i)$ and $P_f(x_f, y_f, z_f)$ be the initial and final points of the end effector in a pick-and-place operation, where x_i, y_i, z_i and x_f, y_f, z_f are the coordinates of P_i and P_f with respect to the reference frame $O - xyz$. When the pick-and-place operation is planned in an environment free of obstacles, it is not in principle necessary to specify the Cartesian trajectory that will be followed by the end-effector because only the initial and final points are relevant to the task to be performed. However, it is preferable to insert a lift-off point P_2 and a set-down point P_{f-1} on the path so that

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