

# Minimum cost trajectory planning for industrial robots

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Received 18 August 2003; accepted 24 February 2004

Available online 27 March 2004

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## Abstract

We discuss the problem of minimum cost trajectory planning for robotic manipulators. It consists of linking two points in the operational space while minimizing a cost function, taking into account dynamic equations of motion as well as bounds on joint positions, velocities, jerks and torques. This generic optimal control problem is transformed, via a clamped cubic spline model of joint temporal evolutions, into a non-linear constrained optimization problem which is treated then by the Sequential Quadratic Programming (SQP) method. Applications involving grasping mobile object or obstacle avoidance are shown to illustrate the efficiency of the proposed planner.

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*Keywords:* Robotic manipulators; Motion planning; Obstacles avoidance; Grasping mobile objects; Non-linear optimization

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## 1. Introduction

Due to their great ability of speed and precision and their cost-effectiveness in repetitive tasks, industrial robots have been used for decade in place of human workers in automatic production lines. But these powerful machines are hardly autonomous in the sense that they require preliminary actions, such as calibration or motion planning, to achieve specified tasks. In general, robotic manipulators are used at their limit capacities for obvious reasons of productivity. This leads, however, to quite significant joint torque and velocity magnitudes which can be harmful to the system state. In order to increase the manipulator performances, it is highly desirable to control the system dynamic taking into account technological, geometrical and environmental constraints as well as any other constraints inherent both to the robot design and to the nature of the task to be executed. Since many different ways are possible to perform the same task, this freedom of choice can be exploited judiciously to optimize a given performance criterion.

During the past decades, a great deal of attention has been given to the problem of motion planning and control. The complexity of the problem made researchers divide the robot control structure into two levels (Fig. 1) (Dombre and Khalil, 1988; Bessonnet, 1992; Angeles, 1997; Chettibi, 2001): the upper level, called *path* or *trajectory planning*, and the lower level, called *path tracking* or *path control*. Path control is the process that makes the robot actual position and velocity match some desired values provided to the controller by the trajectory planner. The trajectory planner receives a description of the path from which it computes a time history of desired positions and velocities. Then, the path tracker compensates for any deviation. In many publications dealing with motion planning of robotic manipulators, authors state a variety of problems and suggest a large diversity of solution schemes. Several regrouping can be done according to execution modes, adopted models for the robot behaviour and proposed numerical methods of treatment.

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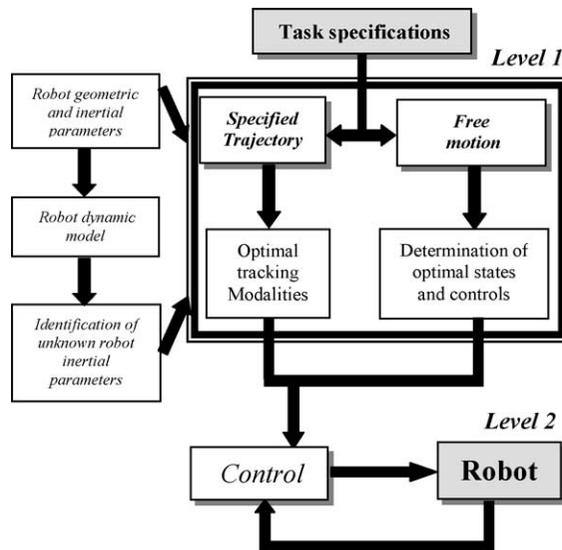


Fig. 1. Synoptic diagram of optimal motion planner for robotic manipulators.

Among the tasks which robot manipulators are devoted to, a first distinction can be made in regards to the desired motion nature. Depending on the robot task, it might be necessary to specify the end effector trajectory in the work space. For example, if the effector's tool acts without interruption according to a predefined path (gluing, arc welding, laser cutting operations, etc.), the planner (or optimization process) defines optimal tracking modalities of the imposed path. On the other hand, in point to point motions (pick-and-place operations, point to point welding), the end effector is free to move between two extremal positions. In this case, the planner tries to define the optimal trajectory and the corresponding controls. A second distinction can be made according to the type of model used. Earlier works (Kahn and Roth, 1971; Luh and Walker, 1977; Luh and Lin, 1981) use kinematic models where the imposed trajectory is geometrically defined in the work space in such a way that the manipulator avoids existing obstacles. The main preoccupation being obstacle avoidance, the optimization problem is synthesized using the inter-penetration distance between elements in collision. Of course, this type of trajectory planning can produce very high execution velocities, particularly when transfer time is minimized. It induces also excessive torque amplitudes which can be harmful for the system state. For these reasons, dynamic models were later incorporated for a more realistic control of the robot dynamic behavior (Bobrow et al., 1985; Pfeiffer and Rainer, 1987; Eltimsahy and Yang, 1988; Yamamoto and Ozaki, 1988; Jaques et al., 1989; Bessonnet, 1992; Chettibi, 2000). However, the problem of motion planning becomes quite complex and requires specific schemes for its treatment. Fig. 2 shows examples of such schemes, some of which are widely used. Two main families can be distinguished: direct and indirect methods (Hull, 1997; Betts, 1998).

Indirect methods are based, in particular, on Pontryagin Maximum Principle (PMP) (Pontryagin et al., 1965) which was first used to define the optimal control. The corresponding states may be obtained by another method. For example, the phase plane method is among early techniques taking into account the robot dynamic model and bounds on joint torques (Bobrow et al., 1985; Kang and McKay, 1986; Shin and McKay, 1986; Pfeiffer and Rainer, 1987; Jaques et al., 1989). It was first used to solve minimum time motion problems along specified paths. Then, it was extended to handle free motions as well (Shiller and Dubowsky, 1986). In this minimum time trajectory planner, it is assumed that the desired path is given in a parameterized form (e.g., using curvilinear abscissa) which is substituted into the manipulator dynamic equations to give a set of second order differential equations in terms of the path parameter. Consequently, bounds on individual joint torques are converted into bounds on parametric accelerations. The allowable sets of second derivatives (one set per joint) are intersected to give a single allowable set. Using the fact that the minimum time solution will be bang-bang in the acceleration, it is possible to construct phase plane plots (Bobrow et al., 1985; Shin and McKay, 1986; Pfeiffer and Rainer, 1987; Chettibi and Yousnadj, 2001) which give the optimal trajectory in terms of the trajectory parameter and its derivatives. Despite the fact that this technique is elegant and solves the optimal time motion planning problem, the discontinuous nature (bang-bang) of joint torques thus obtained creates many practical problems. In fact, the controller must work in saturation for long periods. Hence, the optimal control leaves no control authority to compensate for tracking errors caused by either unmodelled dynamic or delays introduced by the on-line feedback controller. In addition, this method only takes into account constraints that can be formulated in terms of the trajectory parameter and its time derivatives. Therefore, it spans a small field of possible constraints.

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