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Feedrate planning for machining with industrial six-axis robots

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ABSTRACT

Nowadays, the adaptation of industrial robots to carry out high-speed machining operations is strongly required by the manufacturing industry. This new technology machining process demands the improvement of the overall performances of robots to achieve an accuracy level close to that realized by machine-tools. This paper presents a method of trajectory planning adapted for continuous machining by robot. The methodology used is based on a parametric interpolation of the geometry in the operational space. FIR filters properties are exploited to generate the tool feedrate with limited jerk. This planning method is validated experimentally on an industrial robot.

1. Introduction

Over the last four decades industrial robots were used to realize many industrial tasks like material handling, welding, cutting and spray painting. Nowadays they are widely used in many fields of industry, like automobile industry and aircraft industry. Compared to machines tools, industrial robots are cheaper and more flexible with more important workspace. This is why industrials are enthusiastic to replace machine-tools by robots. These industrial robots can carry out machining applications like, prototyping, cleaning and pre-machining of cast parts as well as end-machining of middle tolerance parts. This kind of applications requires high accuracy in positioning and path tracking. Unfortunately industrial robots were designed to realize repeatable tasks. So they are repeaters but not that accurate. The robot repeatability ranges typically from 0.03 to 0.1 mm, and the accuracy is often measured to be within several millimeters (Damak, Grosbois, & De Smet, 2004). Due to their serial structure, articulated robot has lower stiffness than classical machine-tools. The stiffness of an industrial robot is usually less than 1 N/μm, while the stiffness of machines tools is often greater than 50 N/μm (Pan, Zhang, Zhu, & Wang, 2006). This poor accuracy and stiffness are caused by many factors, such as geometric parameter errors: manufacturing tolerances, wear of parts and components replacement, as well as non-geometric factors, such as flexibility of links and gear trains, gear backlashes, encoder resolution errors and thermal effects (Elatta, Pei Gen, Liang Zhi, Daoyuan, & Fei, 2004; Khalil & Dombre, 2004; Shiakolas, Conrad, & Yih, 2002).

Many fields of investigation are proposed to increase the accuracy of industrial robots like; robots calibration, process development and control system. Robot calibration improves the accuracy of positioning by reducing the deviation between the commanded pose and the real one. The complete procedure of robot calibration basically consists of four stages: modeling, measurement, identification and compensation (Meng & Zhuang, 2007). A kinematic model of a robot is the mathematical description of its geometry and motion. To construct this model Denavit-Hartenberg convention is usually used. In kinematic calibration, geometric defaults are modeled and compensated. In this method robot joints are assumed to be perfectly rigid (Elatta et al., 2004). On the other hand, in non-kinematic calibration, flexibility of robot joints and the other non-geometric defaults are taken into account (Ostring, Gunnarsson, & Norrlof, 2003; Ziaei, Liya, & Wang, 2009). In Abele, Weigold, & Rothenbücher (2007), authors have worked on modeling the Cartesian compliance of an industrial robot according to its joints compliance to analyze the system's stiffness. Other works were interested in the machining process itself, like in Pan et al. (2006) where the authors show the effect of the conditions of the machining process on its stability. Regarding the control field, a large number of works have been done on trajectory planning, feedback control, system compensation and feedforward control (Goto, Usui, Kyura, and Nakamura, 2007; Huey, Sorensen, & Singhose, 2008; Hakvoort, Aarts, van Dijk, & Jonker, 2008; Lambrechts, Boerlage, & Steinbuch, 2005). Trajectory planning is one of the important control aspects. It is a fundamental problem in robotics. A well-planned trajectory guaranties a good path tracking and excites less the mechanical

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structure of the robot and the servo control system, so vibrations can be avoided. For the machining applications these vibrations damage the quality of the machined surfaces.

Trajectory planning can be defined as: determining a temporal motion law along a given geometric path, with respecting certain kinematic and dynamic limits. Therefore, from a geometric path, the planner generates the temporal references of position, speed and acceleration for each joint. For industrial robots, the end-effector trajectory can be planned in both joint space and Cartesian space (operational space). Classically, motion planning in joint space is more used. This approach has many advantages like: both joints actuators and dynamic constraints are in the same level (joint level), so the verification of the respect of these constraints is easier for the control system which, in robotics, acts on the joints actuators rather than the end-effector. Trajectory planning in the joint space allows avoiding the problems arising with kinematic singularities and manipulator redundancy (Gasparetto & Zanotto, 2008). The main disadvantage of planning the trajectory in the joint space is that the performed motion by the robot end-effector is not easily foreseeable. This is due to the non-linearities introduced when transforming the trajectories of the joints into the end-effector trajectory through direct kinematic model. This strategy is suitable for classical tasks like, pick and place, where the movement of the end-effector is free between the two extremes positions (Chettibi, Lehtihet, Haddad, & Hanchi, 2004); on the other hand, for machining applications, controlling the feedrate of the cutting tool is indispensable. Planning the trajectories in Cartesian space allows to impose the desired motion law, thus, to control the cutting tool movement. This approach is classically used to plan cutting tools trajectories for the machines tools (Erkorkmaz & Altintas, 2001).

In this paper, a strategy of trajectory planning in robot operational space is introduced. This strategy is adapted to plan trajectories of end-effector of industrial robot intended to realize machining processes. In this method, a smooth motion law is generated by means of a parametric speed interpolator. This interpolator makes advantage of the properties of finite-impulse response (FIR) filters (Kong & Yang, 2005) to give a smooth pattern to the feedrate profile (jerk limited or others). To illustrate the efficiency of this method, trajectories resulting from this strategy are tested on a machining industrial robot, depicted in Fig. 1.

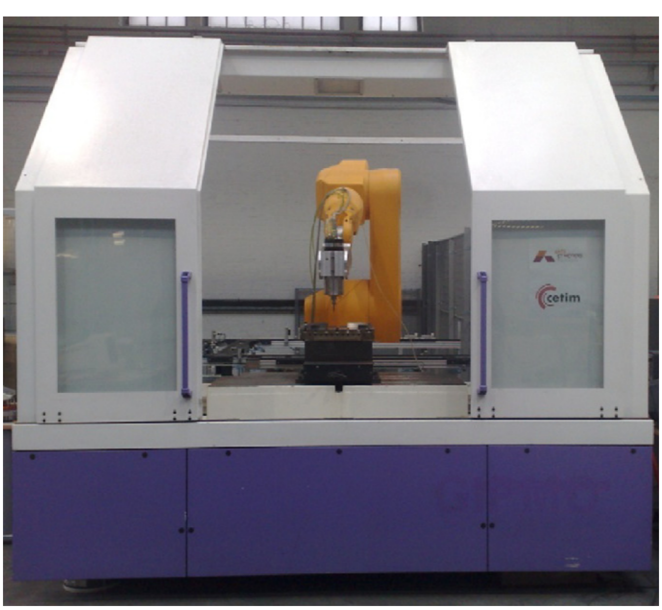

Fig. 1. Machining robot with high-speed spindle.

2. Cartesian space motion planning strategy

As mentioned before, this paper is interested in machining applications by industrial robots. So, unlike other applications it is concerned with planning of continuous-path motions instead of point-to-point motions. In this section, a method of trajectory generation for planning the motion of the cutting tool along a prescribed path is presented. This planning is realized in the Cartesian space. The procedure used to generate motion commands is as follows. Firstly, the motion of the cutting tool on a parametric curve is planned by using a smooth feedrate profile (with different jerk patterns). Secondly, the parametric interpolator generates the position of the cutting tool (end-effector) at each sampling time. Thirdly, these sampled Cartesian positions are converted into joint coordinate commands by using the inverse kinematics model. Fourthly, the joint kinematics constraints, expressed by means of upper bounds on speed, acceleration and jerk are checked and if necessary the feedrate is adapted. Finally, the joint space trajectories are used as references for the joints servos. Fig. 2 illustrates the flowchart of the motion planning strategy detailed in this section.

2.1. End-effector feedrate planning algorithm

The generation of end-effector smooth motion is divided into two steps. In the first step, simple trapezoidal speed profiles are generated. These profiles are filtered in the second step by a finite-impulse response filter.

Motion planning is usually divided into: acceleration stage, constant speed stage (the desired feedrate, denoted F_d, if reachable) and deceleration stage. Considering classical trapezoidal velocity profile and noting F_k the feedrate at time $t=kT_s$, the feedrate evolution during the acceleration stage is given by

$$F_k = F_0 + A_M\, k\, T_s \tag{1}$$

where T_s is the sampling time, k is the sampling number, F_0 is the start feedrate and A_M is the kinematic constraint on the maximum

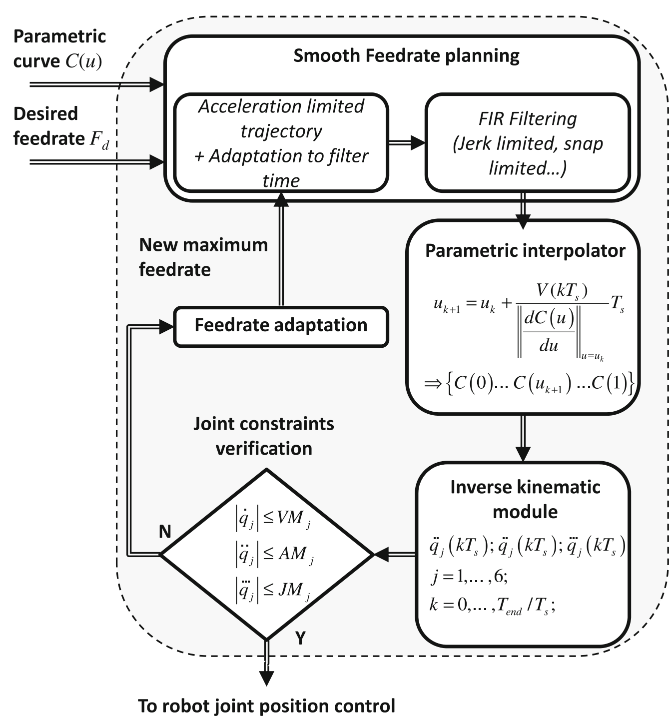

Fig. 2. Cartesian space motion planning strategy.