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Efficiency evaluation of robots in machining applications using industrial performance measure

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ABSTRACT

The paper is devoted to the robotic based machining. The main focus is made on robot accuracy in milling operation and evaluation robot capacity to perform the task with desired precision. Particular attention is paid to the proper modeling of manipulator stiffness properties and the cutting force estimation. In contrast to other works, the robot performance is evaluated using the circularity norm that evaluates the contortion degree of the benchmark circle to be machined. The developed approach is applied to five industrial robots of KUKA family, which have been ranked for several machining tasks. The validity of the proposed technique was confirmed by experimental study dealing with robot-based machining of circular grooves for several workpiece samples and different locations.

1. Introduction

High-speed machining is quite a new application of industrial robots since previously they were mainly used in automotive manufacturing, for part handling and welding [1,2] . As follows form related study [3], the machining segment represents less than 5% of the total market of the industrial robots, but the share is continuously increasing. So, replacement of conventional CNC machines by more competitive industrial robots becomes more and more attractive. The main restraint here is rather limited knowledge of robotics by potential customers and lack of competence of the of robotic cell end-users. Besides, replacing CNC machines by robots leads to additional management expenses. On the other side, the research labs have already confirmed that CNC machines replacement by robots gives essential benefits (reduced product cost, increasing of the work-cell flexibility), which must be clarified for practicing engineers. For this reason, this paper proposes an industry oriented technique for evaluation of the robot capacities in machining, which can be used as the base for the related comparison study.

Compared to conventional CNC machines, robots are able to process complex bulky 3D shapes and provide large and easily extendable workspace that can be modified by adding extra axes. Besides, the same workspace can be shared by several robots. However, the robot trajectory generation is much more complex task compared to the Cartesian machines since mapping from the actuator space to the operational space is highly non-linear. Nevertheless, the results obtained for the tool path optimization of CNC machines [4–7] can be also applied to robotic cells. Another difficulty may arise because of robot redundancy with respect to the technological process. In fact, conventional machining process requires 5 dof only while most of industrial robots have 6 actuators. This redundancy can be used to optimize the tool path, to improve the trajectory smoothness [8] or to reduce the joint torque in order to minimize the impact of machining forces on the robot behavior [9,10].

Another difficulty of robot application in machining is related to non-negligible compliance of robotic manipulators available on the market. For instance, in some cases the end-effector deflections due to the influence of the cutting forces may overcome 10 mm [11]. To reduce them, robot manufacturers pay particular attention to improvement of manipulator stiffness and compensation of the compliance errors using dedicated mechanism and/or special control algorithms. To improve the manipulator stiffness, designers are obliged either to increase the link cross-section or to use advanced composites materials. It is clear that the first solution leads to increasing of manipulator moving masses and consequent reduction of dynamic properties. In contrast, utilization of composite materials essentially influences on the

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robot price and decreases its market competitiveness. Nevertheless, both ways improve the link stiffness only, while the major manipulator elasticity is often concentrated in the actuator gears [12] and can be hardly improved in practice. Another method of the compliance error reduction is based on the mechanical gravity compensators (pneumatic, hydraulic, spring-based, etc.), which produce auxiliary forces/torques reducing impact of the link weights. However, this solution does not allow compensating the impact of the machining forces but only shifts the force-deflection relation. To overcome the problem of elastic deformations in the actuator gears, robot manufactures tends to use secondary encoders attached to the motor shaft [13] that allows to modify the actuator input in order to compensate the gear compliance. It is obvious that this approach also increases the robot price. According to our experience, the double encoders enable compensating about 65% of the compliance errors on average, but in some workspace areas the compensation level is limited by 40–50%. The main reason for this is that the robot link deformations are outside of the double encoder observability. It is clear that for the high-speed milling, where the cutting forces are high enough to cause deflection of several millimeters, such level of error compensation is not enough sufficient. In this case, it is reasonable to apply the off-line error compensation technique [14–16] based on the modifying the target trajectory used as the controller input. As follows for our previous research, this approach is very efficient. In particular, the off-line technique based on the simple (reduced) manipulator stiffness model allows user to compensate 85–90% of the end-effector deflections [12,17,18], while the complete stiffness model ensures the compensation level of about 95%[19]. However, it should be stressed that usually robot manufacturers do not provide customers with the manipulator stiffness parameters, so they must carry out dedicated experimental study to obtain the desired model [18,20–23]. In this paper, the above mentioned problem will be also considered.

To advance robot application in machining, end-user should be provided with clear and efficient tool allowing to evaluate the final product quality expressed via the level of the end-effector deflections caused by the manipulator elasticity. These deflections can be computed both for a single work point and given force/torque or for a set of given trajectories and corresponding cutting forces [24]. It is clear that usual approach based on different indices extracted from the Cartesian stiffness matrix [21,25,26] are not suitable here. In particular, commonly used performance measures based on the stiffness matrix singular values do not represent directly the machining accuracy which is the primary indicator for practicing engineers. For this reason, this paper proposes an industry oriented technique allowing to examine particular robot suitability for a give machining task and to compare several robot-based implementations.

To address the above mentioned problems, the reminder of the paper is organized as follows. Section 2 deals with the particularities of the robot based machining. Section 3 presents stiffness modeling background for industrial robots. Section 4 introduces industry-oriented performance measure adapted for machining accuracy evaluation. Section 5 contains comparison analysis of several industrial robots available on the market that are suitable for high-speed machining. Section 6 deals with experimental validation of the main theoretical results. In Section 7, the limitations of the proposed approach and perspectives are discussed. Finally, Section 8 summarizes the main contributions of the paper.

2. Robot-based machining

2.1. Particularities of machining with robots

Machining with robots is an intersection of two engineering fields: conventional machining and robotics. Machining sector usually prefers for these operations Cartesian CNC machines, which provide end-users with high reliability, good repeatability (2 μm) and very good precision (5 μm) [27]. Traditionally, they are used for processing of metal parts from parallelepiped-like crude products with high material removal rate. These operations are quite popular in automotive industry, aeronautics as well as in mold making, prototyping, etc. Contemporary CNC machines possess quite large workspace allowing essentially increase an application area. Besides, their efficiency was also proved for processing of composite materials that are utilized more and more due to perfect mass-to-strength ratio. In addition to milling, finishing and trimming operations can be also performed by CNC machines at present. Nevertheless, in spite of numerous advantages, the CNC machines remain very expensive and their workspace is limited and cannot be extended, which is crucial for aeronautic and shipbuilding. This motivates users to find an alternative solution.

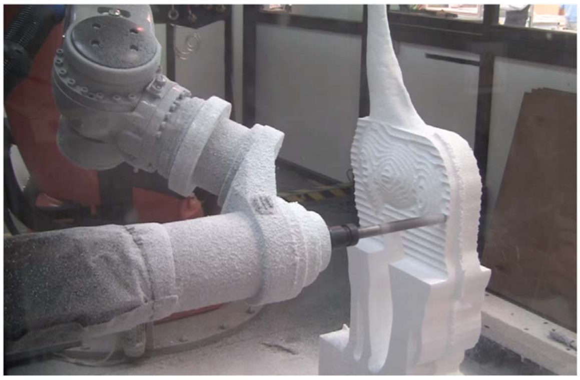

Fig. 1. Example of machining process with robot.

One of the promising ways to overcome the above mentioned difficulties is replacing the CNC machines by industrial robots, whose cost is competitive and workspace can be easily extended (by adding extra actuated axes). An example for such an application is presented in Fig. 1. It worth mentioning that machining is fairly new application for robots. Traditionally, the market of industrial robots is shared between handling, pick and place, assembling and welding. The processing (including machining), represents insignificant part of the market, less than 5%. According to PWC study [28] this shares will remain the same in nearest future, as still there are a lot of pick and place operations to be automated with the improvement in robotic vision. Nevertheless, the share of robot-based machining is continuously growing and about a quarter of new robotic cells in North America are processes oriented ones. Large part of this market share corresponds to trimming that was traditionally a high-qualified manual work, but nowadays the robots become competitive here due to increasing of their accuracy. For machining, robots are attractive due to their large and extendable workspace and competitive price that makes them a cost-effective solution for machining of large dimension parts. However, the main obstacle for robots utilization in machining is their relatively low accuracy (about 0.7 mm) and repeatability (about 0.2 mm) compared to the CNC machines, assessment of robot capability for this application have been explored by Slamani et al. [29,30] with several methods. It worth mentioning that under the cutting force influence, the positioning errors can reach up to several millimeters. Nevertheless, there are a number of efficient solutions to reduce manipulator positioning errors that were discovered in research labs and progressively applied in industrial environment. The latter allows robots to compete with CNC machines in terms of accuracy, while providing essentially larger workspace. In more details, comparison of CNC machines and robots for machining is presented in Table 1.

2.2. Cutting forces in machining

The problem of the cutting forces evaluation is in the focus of mechanical engineers more than 70 years. In his pioneer work, Merchant used principle of minimum angle to develop an analytical