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IFAC-PapersOnLine 49-12 (2016) 174–179

Experimental study of robotic-based machining

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Abstract: The paper is devoted to the experimental study of robotic based machining for several industrial robots. Particular attention is paid to the robot precision in milling operation and its ability to perform the task with desired accuracy. In contrast to other works, the robot performance is evaluated using the circularity norm that evaluates the contortion of the benchmark circle to be machined. The developed approach is applied to five industrial robots of KUKA family. The validity of the proposed technique was confirmed by experimental study dealing with robot-based machining of circular grooves.

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Keywords: Robot-based machining, industrial robot, circularity, milling, stiffness model.

1. INTRODUCTION

High-speed machining is quite a new application of industrial robots since previously they were mainly used for part handling and welding (Kochan, 2004). As follows form related study (Chen and Dong, 2013), the machining segment represents less than 5% of the total industrial robots market, but the share is continuously increasing. So, replacement of conventional CNC machines by more competitive industrial robots becomes more and more attractive. For this reason, the paper proposes a comparison analysis for typical industrial robots used in machining application.

In contrast to conventional CNC machines, robots are able to process complex 3D shapes and provide large and extendable workspace. However, the robot trajectory generation is more complex task compared to the Cartesian machines since mapping from the actuator space to the operational space is highly non-linear. Another difficulty may arise because of robot redundancy. In fact, conventional machining process requires 5 d.o.f. only while most of industrial robots have 6 actuators. This redundancy can be used to optimize the tool path, to improve the trajectory smoothness or to reduce the joint torque (Vosniakos and Matsas, 2010).

Another difficulty of robot application in machining is related to non-negligible compliance of robotic manipulators. For instance, in some cases the end-effector deflections due to the influence of the cutting forces may overcome 10 mm (Matsuoka et al. , 1999). 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 reduction of dynamic properties. In contrast, utilization of composite materials essentially influences on the robot price. Nevertheless, both ways improve the link stiffness only, while the major manipulator elasticity is often concentrated in the actuator gears (Dumas et al. , 2012). Another method of the compliance error reduction is based on the mechanical gravity compensators. However this solution does not allow compensating the impact of the machining forces. To overcome the problem of elastic deformations in the actuator gears, robot manufactures tends to use secondary encoders attached to the motor shaft (Devlieg, 2010) that allow to modify the actuator input in order to compensate the gear compliance. According to our experience, the double encoders enable compensating about 65% of the compliance errors on average. 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 sufficient. In this case, it is reasonable to apply the off-line error compensation technique (Chen et al. , 2013, Gong et al. , 2000) based on the modifying the target trajectory. As follows for our previous research, this approach is very efficient and may ensure the compensation level of about 95% (Klimchik et al. , 2015).

To advance robot application in machining, end-user should be provided with clear data 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 estimated both for a single work point and given force/torque or for set of given trajectories and corresponding cutting forces. It is obvious that usual approach based on different indices extracted from the Cartesian stiffness matrix (Guo et al. , 2015, Nagai and Liu, 2008) are not suitable here. 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.

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10.1016/j.ifacol.2016.07.591

2. ACCURACY OF ROBOT-BASED MACHINING

2.1 Industrial standards for machining accuracy

In industrial practice, there exist a number of norms to evaluate the quality of a final product. They estimate the path straightness (ISO 12780), the surface flatness (ISO 12781) and the path roundness (ISO 12181), which is also called the circularity. From our experience, the circularity norm is the best suited one for the machining process, since it also evaluates the straightness and flatness in indirect way. In fact, the straightness violation leads to the non-uniform circle stretching/shrinkage and the flatness violation causes the circle twisting. On the other side, perfect milling of circular profiles guarantees perfect machining of straight lines and plain surfaces. For this reason, the circularity norm will be used further to evaluate the capacity of industrial robot to perform the machining tasks.

According to relevant standard (ISO 12181), the circularity calculation includes two steps: building a reference circle and estimating the deviations with respect to the reference circle. The standard defines four methods to obtain the reference circle that are called respectively the Minimum Circumscribed Circle (MCC), the Maximum Inscribed Circle (MIC), the Minimum Zone Circles (MZC) and the Least Squares Circle (LSC). The difference between these methods is illustrated in Fig. 1. In all cases, the circularity is equal to the distance between the inscribed and circumscribed circles. The principal difference is related to the center that is computed using different approaches. For example, for MIC the center point is computed for the maximum inscribed circle and it is also used for the minimum circumscribed one. In the MCC method, the center is computed for the minimum circumscribed circle and the inscribed circle is build using the same center point. In the case of LSC, the inscribed and circumscribed circles are found for the center point obtained for the least square circle. In contrast, the MZC method uses a center point for which the distance between the inscribed and circumscribed circles is minimal. It should be stressed that in the case of real measurement data all methods are competitive and provide almost the same results (Li and Shi, 2009). However, MIC and MCC methods are not applicable if machining profile is asymmetrical. In this case it is prudent to use either MZC or LSC methods. In fact, the MZC evaluates true circularity; however it is the most complicated approach from numerical point of view. Thus, a reasonable alternative in engineering practice is the LSC method. Advantages of this method are confirmed by simulation results presented in Fig. 2, which show that difference between MZC and LSC is negligible in the case of conventional cutting conditions (Calvo and Gómez, 2015).

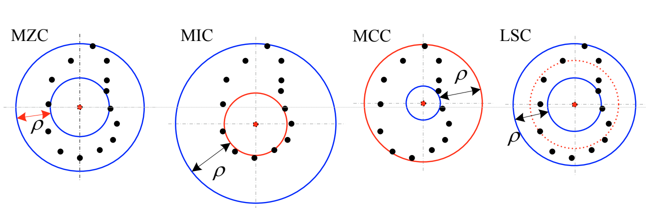

Fig. 1. Estimation of the circularity: definition of ISO norms.

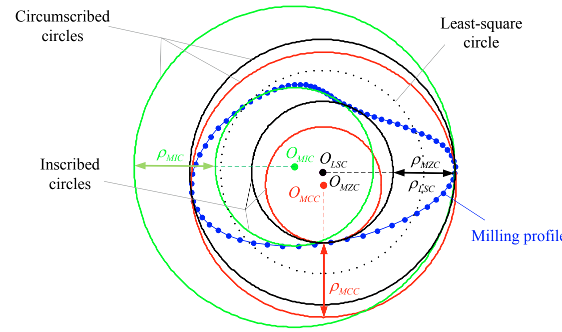

Fig. 2. Difference between the circularity norms.

2.2 Evaluation of circularity for robot-based machining

Basic expressions. As it was mentioned above, the circularity is the performance measure that characterizes the difference between the radii of maximum inscribed and minimum circumscribed concentric circles obtained for the reference machining profile

$$\rho = r_{\max} - r_{\min} \tag{1}$$

In the frame of the LSC method, the center point is obtained by solving the following optimization problem

$$\sum_{i=1}^{n} \left(\sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} - r\right)^2 \to \min_{x_0,\, y_0,\, r} \tag{2}$$

where (x_i, y_i) are the coordinates of the machining profile provided by the measurement system, (x_0, y_0) is the desired center of least-square circle and r is its radius. The optimization problem (2) is highly non-linear one and it cannot be solved analytically. For this reason, the Newton–Raphson method is used.

After finding the center point (x_0, y_0), the desired radii of the circumscribed and inscribed circles are be computed as

$$r_{\max} = \max(|\mathbf{p}_i - \mathbf{p}_0|, i = \overline{1,n}); \qquad r_{\min} = \min(|\mathbf{p}_i - \mathbf{p}_0|, i = \overline{1,n}) \tag{3}$$

where $\mathbf{p}_i = (x_i, y_i)^T$ are the measurement profile point and $\mathbf{p}_0 = (x_0, y_0)^T$ is the center of corresponding least-square circle. Hence, for given set of points $\mathbf{p}_i$ describing machining profile one can compute the circularity index ρ using expressions presented above. It is clear that these points can be obtained either experimentally or numerically, using relevant models of the manipulator. This paper concentrates on the approach that requires the manipulator stiffness model.

Modeling of the machining profile. This approach assumes that all geometric and elastic parameters of the manipulator are given. In this work, the circularity is evaluated for the benchmark profile corresponding to a circular milling task of the radius 100 mm. This benchmark is in a good agreement with typical industrial requirements, but it can be easily adapted to other dimensions.

Assuming that machining produces the cutting force/torque $(\mathbf{F}, \mathbf{M})$, the manipulator end-effector deflections $\Delta\mathbf{t}_i$ caused by this loading can be computed using expression

$$\Delta\mathbf{t}_i = \mathbf{J}_\theta(\mathbf{q}_i) \cdot \mathbf{K}_\theta^{-1}(\mathbf{q}_i) \cdot \mathbf{J}_\theta^{\mathrm{T}}(\mathbf{q}_i) \cdot \begin{bmatrix} \mathbf{F}_i \\ \mathbf{M}_i \end{bmatrix} \tag{4}$$

where the subscript "*i*" indicatives the machining profile point number, $\mathbf{K}_\theta(\mathbf{q}_i)$ is the manipulator stiffness matrix corresponding to the configuration $\mathbf{q}_i$, $\mathbf{J}_\theta(\mathbf{q}_i)$ is the

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