Milling with industrial robots: Strategies to reduce and compensate process force induced accuracy influences

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Abstract

Industrial robots offer a good basis for machining from a conceptual point of view. However they are rarely utilized for machining applications in industry due to their low stiffness and the bad achievable work piece quality. Available solutions using position control of the tool require costly additional hardware and measurement equipment; force controlled solutions depend on low level controller access that is not commonly available for generic cell setups. This paper proposes a three-step approach to compensate for process force induced accuracy errors: (1) selection of appropriate milling strategies and cutting parameters, (2) an offline compensation of the force induced deviations and (3) a respective online compensation method. Experimental validation of the results has been performed for the first two steps.

1. Introduction

Using industrial robots for machining applications offers a number of benefits compared to the use of conventional machine tools, especially in applications where the latter cannot exploit their full potential [1]. On the other hand the structure of typical 6-DOF industrial robots with serial chain kinematics is less stiff than the one of a dedicated machine tool and thus robots are much more sensitive to forces induced by the machining process.

This paper introduces an approach to improve the geometrical accuracy in machining applications with industrial robots. Focus of the approach is the modelling and compensation of the forces induced by the machining process. Although machining process forces are only determinable up to a certain degree of accuracy, parts of the compensation are already applied offline during robot program generation. This procedure is chosen in order to reduce the corrections necessary during execution of the machining as well as to reduce the need for additional measurement equipment.

The presented approach especially addresses machining in hard materials, like hardened steel or inconel. These materials are typically not machined with robots due to the poor achievable work piece quality, which to a great extend is a result of the process force influence. The presented compensation procedure is based upon the physical capabilities of the robot itself. This has some drawbacks in terms of maximum reachable accuracy and reaction time, but is justified by the effort to benefit ratio. In [2] a compensation approach using an external actuation mechanism was presented. While improving the performance of the overall system, such a solution also results in significantly increasing hardware costs and integration efforts and thus is contrary to the idea of realizing cost-effective machining by using industrial robots.

Machining induces process forces with high frequencies. Due to the limitations of the robots interpolation cycle, high frequent oscillations cannot be compensated, but as the main part of the geometric deviation is caused by the low frequent mean value of the force this is still reasonable (nevertheless sources of high frequent errors like chatter are addressed in step 1 of the compensation approach). Other approaches, like [3] and [4], make use of low level interaction with the robot controller, using open controllers or controller extensions, which allow faster adaption of the path, but unfortunately are not applicable to most standard industrial setups.

The proposed approach is divided into three steps, whereof two are already applied offline, which means, that they do not require any additional equipment to be added to the robot: In the *first step* special milling strategies and appropriate process parameters for the use with industrial robots are applied. Hereby problematic process conditions and unfavourable robot poses are avoided, providing the best possible basis for the follow up steps. In the *second step*, which is applied during generation of the robot program, force induced deviations are calculated and compensated for. This requires both, a model of the cutting force and a model of the robot's stiffness; in this paper we focus on the modelling of the cutting force. To cover the non-deterministic parts of the cutting force and to deal with tolerances and errors in the real process, in the *third step* an additional online compensation is applied also. Using the same model information as in the previous steps, but measuring the actual force, remaining deviations can be identified and compensated for.

This paper is organized as follows: Modelling of the process forces determination of the required material and tool parameters is described in Section 2. In Section 3 the usage of that model during the three steps of the compensation procedure is explained. The experimental setup and the results of the experimental validation can be found in Section 4. The paper ends with conclusions and future work topics in Section 5.

2. Modelling the process force

2.1. Process force calculation

The process force calculation is based on the theoretic fundamentals of *Kienzle* [5], which is a frequently used outset for cutting force models (see, e.g. [6]). The process force is defined as the sum of the force vectors $\{F_c, F_f, F_p, F_a\}$ during the active cut, as described in [7]. As the cutting performance is the result of the product of the cutting force F_c and the cutting velocity v_c, the cutting force itself can be calculated as the product of surface A and the specific cutting force k_c (1). The equation (2) shows that the specific cutting force decreases with increasing chip size h_m.

$$F_c = a_p \cdot f_z \cdot k_c \quad (1)$$

$$k_c = k_{c1.1} \cdot \frac{1}{{h_m}^m} \quad (2)$$

The chip size can be calculated by the product of the cutting depth a_p and the cutting velocity per tooth f_z but as there is a variety of tool shapes it depends also on the shape of cutting edge. The cutting edge of an end mill describes a cycloid curve due to the superposition of the feed forward and the rotation move. For the described approach this superposition was approximated to a circle curve as the high complexity is not needed for small f_z. The here highlighted equation (3) is used for flat end mills to determine the chip size for changing entry ρ_e and exit angle ρ_a. For other mills this curve has to be adapted to represent the actual movement of the cutting edge.

$$h_m = \frac{1}{\rho_a - \rho_e} \int_{\rho_e}^{\rho_a} f_z \cdot sin(\rho)\, d\rho \quad (3)$$

Equation (4) is used to calculate the final feed forward force.

$$F_f = \frac{1}{4}\left(2\rho - sin2(\rho) - 2cos^2(\rho)\right) + C \quad (4)$$

Yet this approach does not take into account the hyperbolic turn of the cutting edge as this fact has only insignificant influence. The same applies to additional quality factors described by [8] related to the k_c value, like the change of the material properties through the part, the cold work hardening or the cutting temperature due to the cooling situation.

2.2. Retrieving material specific parameters

Many material related parameters are already known today and can be used as input parameters for the process force calculation model. However every year new materials or material combinations enter the market, the respective $k_{f1.1}$ and $k_{p1.1}$ as well as the related m_f and m_p values are often not listed in official tables and these published parameters are related to a specific material-tool combination. As a result of the validation of the first experiments it was decided to develop an approach to automatically retrieve the needed material specific parameters for the desired setup. A test scenario was developed to provide a quick parameter retrieving procedure for the end user.

First the tool-material combination is needed with the advised machining parameter as well as a 6-DOF force/torque sensor. A set of slots has to be milled as shown in Figure 1. The slots change the a_e value along the cut from 1 mm to full cut which in this case were 6 mm, as a 6 mm flat end mill was used. The a_p value changes per slot from 1 mm to 4 mm.

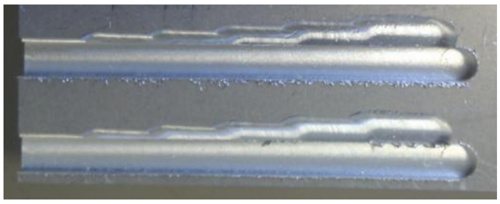

Figure 1. Section of test part to retrieve material specific parameters

The forces measured from the 6 DOF sensor are stored in a csv file. Now the $k_{c1.1}$, $k_{f1.1}$, $k_{p1.1}$ and the related mc, mf and mp are calculated with a line of best fit, generated by the method of least squares, with the know equations published in [5] and [8]. With the retrieved parameters it is possible to calculate forces for every material removal scenario that can appear for that tool-material combination.

3. Compensation approach

3.1. Step 1 – Machining strategy generation

Selecting a strategy which is used with optimized machining parameters is the first step to achieve an improved surface quality. These parameters do not have to be necessarily identical to parameters that would have been used for the same operation on a machine tool. Important conditions that have to be considered are the allocation of the work piece in the robots workspace, eigen frequencies of the robot structure in given configurations, the selection of appropriate feed rates and the number of points considered for trajectory planning in order to generate a stable movement. If possible, axis reversals and situations where axes are discharged of load should be avoided, as then backlash effects can occur.

As the robot is less stiff than a conventional machine tool, the reduction of process forces, especially orthogonal to the feed direction, becomes more important. The force orthogonal to feed direction can be reduced to zero (mean force over one turn of the tool) by selecting a cut-against-feed strategy with the engagement angle of the tool (difference between entry ρ_e and exit angle ρ_a) near half of the tool diameter. This working point varies, depending on the feed rate. By using trochoidal movements, a machining strategy can be generated, that is realising such an engagement angle over the whole tool path.

3.2. Step 2 – Offline force compensation

After optimising the machining strategies, assuring reasonably stable cutting conditions, the compensation of the process force induced deviations can be applied. After generating the tool path, the mean force value for each tool path point can be calculated. With this information, the tool path can be adapted to compensate for the estimated deflection of the robot. It is obvious that some requirements have to be met for this approach to give satisfying results: As the compensation can only be applied per tool path point, a reasonably small distance between these points has to be ensured. On the other hand a high point density may cause the robot controller to either reduce the feed rate or to skip programmed points. The former is not favourable as it may result in an inferior surface quality or in greater tool wear. The latter is directly reducing the quality of the machined part, as the resolution of the tool path is reduced. The minimum distance between the tool path points (D_S in µm) is calculated by

$$D_S = \frac{F \cdot D_T}{60} \tag{5}$$

where F is the maximum required feed rate (in mm/min) and D_T (in ms) is the cycle time of the robot controller. As further requirements the engagement angle of the tool has to be known for each point of the tool path (see Formula (3)) and a stiffness model for the robot has to be available. Stiffness models for industrial robots on joint basis are described e.g. in [9] and [10]. For the experimental validation (see Section 4) of the force compensation a linear stiffness model was assumed. This is acceptable as only a small fraction of the robot's workspace was used and the occurring process forces were small enough to not leave the range where applied force and resulting deflection are linear correlating. The model was parameterised with empirical data from the milling experiments.

3.3. Step 3 – Online force compensation

The pure offline approach can be used to improve the machining accuracy up to a certain level, but cannot cope with high-frequent changes of the force (whereas high-frequent is defined by mean time between two tool path points and thus by the cycle time of the controller) or unpredictable deviations from the assumed cutting conditions (e.g. due to geometrical tolerances of the work piece). Therefore an online correction is added to compensate during machining.

The actual process forces are measured using a force/torque sensor on the robot's TCP. Using the difference between the offline calculated force and the measured force the deviation of the deflection is calculated (using the same stiffness model as in the offline compensation) on an external computation device and looped back as an offset to the robot. The offline calculated force is stored in the robot program as a set of three variables (one for each spatial direction) which are handed over to the external device using outputs of the robot controller. In this way no additional synchronisation between controller and external device is required. By handing over not only the force vector for the current point, but also for one (or more) subsequent points, intermediate interpolation or look-ahead functionalities can be implemented. Mapping of the compensation directions and the coordinate system of the F/T sensor is done via the TCP coordinate system.

The online solution could also be applied as stand-alone compensation, but limitations of the robot controller response time would become more noticeable.

4. Experimental validation

The experimental setup used for validation was chosen to stay close to a situation that is likely at the intended commercial user, where the robot is also used for other tasks. Therefore, no additional cooling system, a commonly available robot and only few external measurement equipment was used.

Experimental validation was carried out using two different materials: Aluminium (EN7075) and hardened steel (1.2343 X37CrMoV5-1). While aluminium was selected as anticipated typical material for robot machining operations, the hardened steel allowed examination of the methodology for more sophisticated materials with noticeable larger process forces. As the experiments were carried out using dry machining or minimum quantity lubrication, a preceding series of machining tests has been carried out on a conventional machine tool to identify reasonable initial cutting parameters. Thereby it was possible to minimise the influence of the dry machining situation and focus on the peculiarities of the robots mechanical structure and controller. The cutting tools are from Hoffmann group Garant (tool no. 206260 and 191634), each with 6 mm diameter.

	v_c [m/min]	s [rpm]	f_z [mm/tooth]	f [mm/min]
EN7075	300	17000	0.03	2040
X37CrMoV5-1	84	4450	0.008	140

Table 1. Experimental determined parameters for dry machining

A robot cell for milling applications was implemented in an existing reconfigurable production cell based on the Smart Robot Tooling Concept introduced in [11]. Center of the setup is a KUKA KR125 robot with a KRC1 controller linked to a programmable automation controller (PAC). A milling spindle providing 3.6 kW at 18.000 rpm is mounted on a fixed support in the cell, but can also be mounted on the TCP of the robot. A 6 DOF force/torque sensor was mounted between the robot TCP and the adapter plate for both concepts providing data to the PAC.

The parameterization for the material specific parameters was done for aluminium EN7075 with the described setup. As the time required to process one tool path point (cycle time) is an important parameter that limits the accuracy of the machined part, the point distribution is related to the desired cutting velocity (here: d=6 mm; v_c=300 m/min; s=15600 rpm; f_z=0.025 mm/tooth; z=4 teeth). In an additional experiment the controller cycle time of ≤45 ms was identified. Therefore the point distribution was set to 0.5 mm (see formula (5)).

$k_{c1.1}$ lit. [N/mm²]	780	m_c lit.	0.23
$k_{c1.1}$ calc. [N/mm²]	776	m_c calc.	0.274
Δ in%	0.5%	Δ in%	19%

Table 2. Specific cutting forces compared

The first result from the experiments was that the k parameters are very close to the ones that can be found in literature, but the m parameters differ about 10 %. Also the assumption of a linear stiffness model for the robot was confirmed (0.1 mm deviation per 10 N). The validation of the adapted machining strategy (where the mean passive force is zero) resulted in 30 % less deviation from the desired geometry. The offline calculated forces showed good correlation with the measurements (deviation up to 15 %).

5. Conclusions and future work

In this paper a three step approach to improve geometrical accuracy for machining with industrial robots was proposed and partially validated.

Future work includes the validation of the offline compensation for generic tool paths (using a joint-based stiffness model, to also consider effects like gear backlash), validation of the online approach and the implementation of the look-ahead functionality.

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