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Enabling an Industrial Robot for Metal Cutting Operations

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Abstract

This paper focuses on a cost-effective manufacturing of large frame parts for aerospace industries with an industrial robot. The main challenge is the low stiffness of a serial kinematic, resulting in positioning errors due to gravity and cutting forces. Therefore, an approach is presented to optimize positioning of a robot by compensation of tool deflection. A static deflection model of the robot is built up to calculate the deflection caused by forces acting on the spindle. To detect these forces a suitable measurement device is presented. This sensing spindle holder is calibrated to detect cutting forces.

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Keywords: machining robot; process monitoring; compensation; force measurement

1. Introduction

Within the research project Innoflex, the weight reduction of aircraft parts by use of new materials like AlCuLi-alloy is analyzed. A further advantage of this material is that it can be extruded to a shape close to the final contour. This reduces the cutting volume and enables the reduction of cutting forces to an optimum for cutting with robots. This might enable an industrial robot for the machining task. Large frame parts today are machined on large gantry machine tools that are expensive. Because of its low price and large working area, more and more industrial robots are used for machining operations. Compared to conventional machine tools, robots are cheaper but not accurate enough to compete against them. Main reason for their poor positioning accuracy is their low static and dynamic stiffness due to high joint compliance and long arms. A non-accurate calibration of the load or changes in the load lead to positioning errors, which are pose dependent. Additional process forces acting on the robot structure lead to further displacements of the tool center point (TCP). Weigold presents these and other effects on the positioning accuracy [1].

Tests show, that the positioning accuracy as well as the trajectory accuracy, which includes dynamic effects, need to be improved for the use in cutting operations.

For this reason, much research has been done to optimize the positioning accuracy. Since gravity forces on the robot structure are pose dependent, they cause deviations of the end effector position without process forces acting on the robot. Eastwood and Webb [2] analyzed the effects of gravity and built a simulation model, which reduces at least 70 % of the mass-induced positioning error. Roth et al. divides robot calibration approaches into three levels [3]. Level 1 is a calibration of joint sensors and drives. The calibration of the kinematic transformation is defined as level 2. This kinematic calibration is used to identify geometry errors resulting from tolerances in the robot arms or their assembling. Hollerbach [4] presents an overview of different approaches of kinematic calibration. As an example Duelen and Schröer [5] describe a kinematic calibration and showed that this calibration can improve the absolute accuracy of the robot up to its repeatability. The third level of calibration is described as “non-kinematic” calibration, which summarizes all errors resulting from thermal effects, compliance of joints and links, backlash and friction in the gearing and compliance in the bearing of the joints as well as dynamic effects.

Today, the calibration in level one and two is done by robot manufactures as well as service providers who do a kinematic calibration to achieve higher positioning accuracy in a defined

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working space. Since, the International Organization for Standardization in September 2012 rejected the DIN EN ISO 9283, there are no standards for robot testing and calibration. The ISO 9283 defined important performance characteristics for robots and recommended tests to achieve them [6]. The standards are based on Schröer, who started an approach to define standard tests generalized for different industrial robots in 1998 [7].

While these approaches calibrate the position accuracy for the robot with constant payload, forces acting on the robot are not taken into account, even though measurements show deflections of up to 2 mm during cutting operation. Thus, the compliance of industrial robots is analyzed in different research projects. Abele et al. presented an approach with a Cartesian compliance map for an industrial robot [8]. Based on measurements of the joint stiffness, the compliance in Cartesian coordinate system is calculated. The approach presented by Nubiola and Bonev [9] and Klimchik et al. [10] deals with a robot manipulator calibration of an ABB IRB 1600 and a Kuka KR-270. The second approach focuses on a procedure for use in industrial environment while the first one is more complex to achieve a higher accuracy.

These results show that the stiffness of the industrial robot is the main reason for trajectory errors during milling operation. Because a force-prediction and offline compensation or a feed-forward control is not precise enough, these forces must be detected online. A force sensor can be placed on the side of the tool or on the side of the workpiece. Typically, a force dynamometer is used, which is placed between the working table and the workpiece. These systems are available on the market for several years and are mainly used in laboratory for cutting tests. Most of these dynamometers base on piezo sensors, which measure the forces or torque at the workpiece. Due to their small size the working area is limited. Furthermore, the manual effort for changing the workpiece is very high, which is one reason why they are not established in industrial application. Some research has been done the last years to implement force sensors to the machine side without limiting the working area and the machine operator during his work [11]. These sensors are mainly used for process monitoring tasks. The sensing device SPIKE by pro micron GmbH was developed to measure torque and axial force acting on the tool. This device uses strain gauges placed at a special tool holder to identify measured values from their signal. Because the sensing is placed on the rotating part, the data is transferred wireless to a monitoring system. Kistler Instrumente AG offers a rotating dynamometer Typ 9171A to their customers for force and torque measurement, which is placed in the tool holder of the spindle and offers a standard HSK tool holder shaft to make tool changes easier. Kistler Instrumente AG and the Institute for Machine Tools and Manufacturing at the ETH Zürich developed a sensing unit integrated in the spindle. Though the sensing device works in laboratory tests [12], it is not on the market, yet. All these measurement devices suffer from a low stiffness high additional weight and integration into the machine control for compensation task is complicated. The effort for integration of these systems is very high which might be a main reason why these systems are not used for compensation tasks.

An approach on how the compensation of compliance is done is presented in section 2. The stiffness of an industrial robot is analyzed with help of a modal analysis. Main results are presented in section 3. Based on the knowledge gained from these measurements, a simulation model was built up to calculate the displacement due to forces acting on the tool center point of the milling robot. Furthermore, the model is used in online compensation of trajectory errors. Therefore a force measurement device is needed. A new force-sensing unit is developed to attain more stiffness without limiting the working space. The force sensing spindle holder is presented in section 4. The calibration and validation of the sensing spindle holder, presented in section 5, is done for a six axes industrial robot.

The main challenge of industrial milling robots is their low positioning accuracy and low stiffness in the gears and bearings of the joints and the structure. Thus, the kinematic transformation cannot determine the tool center point (TCP) of the robot precisely without taking forces and torques acting on each axis into account. Cutting forces lead to a quasi-static force load on the robot. This static force has the main effect on the deflection of the TCP and it is possible to compensate this with the robot. A compensation of higher frequency parts of the cutting force is not realizable with the robot itself since the dynamic is limited. Thus a static compliance model is needed to simulate the deviation of the robot according to the force acting on the TCP. This model is used for offline trajectory programming to calculate the stiffest pose and the best position of the workpiece with help of forces from a cutting simulation. However, process forces might differ from simulation results, thus an online compensation is required that measures the actual force acting on the TCP to rise the trajectory accuracy.

The compensation approach presented in Figure 1 consists of two main components: the robot control and the sensing spindle holder. The robot control is a Siemens Sinumerik control connected to the original control KR C4 of the robot. Main task of these controls is the positioning of the milling spindle according to the programmed trajectory in workspace. The Sinumerik control gives a common machine user interface to the operator and enables g-code programming, known from conventional machine tools. The sensing spindle holder measures forces acting on the TCP and uses this information for a communication between the control and the compliance model.

The force measurement is implemented with use of strain gauges placed at the spindle holder. These strain gauges are

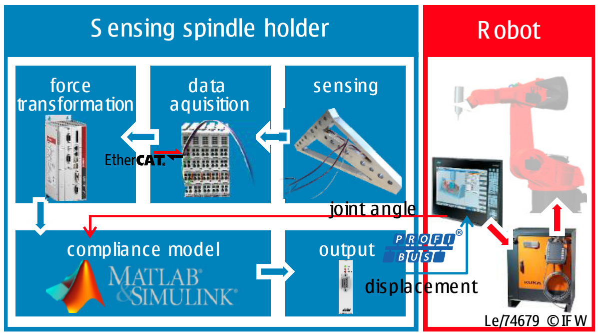

Figure 1: Compensation approach