Experimental Investigation of Sources of Error in Robot Machining

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Abstract. This document is divided into two parts. First a survey is given presenting sources of error in robot machining and outlining their dependencies. Environment dependent, robot dependent and process dependent errors are addressed. The second part analyses the errors according to their source, magnitude and frequency spectrum. Experiments under different conditions represent a typical set of industrial applications and allow a qualified evaluation. This analysis enables the qualified choice of suitable compensation mechanisms in order to reduce the errors in robot machining and to increase machining accuracy.

Keywords: robotic machining, robot dynamics, robot precision, robot compensation.

1 Introduction

Industrial robots (IR) are traditionally used for handling applications. According to the International Federation of Robotics 78% of all industrial robots were used for handling and welding [1]. As the demands for more flexibility and lower costs are rising in industry new concepts have to be developed to satisfy the requirements of modern production. As industrial robots offer lower costs than a conventional tooling machine, an exceptional flexibility and a big working area, more and more industrial robots are used for machining operations. However, so far industrial robots cannot compete with machine tools in the field of high precision. Due to a large set of error sources, industrial robots cannot address the same variety of applications like conventional machine tools. Machine tools are optimized for the machining process by providing high stiffness. Yet industrial robots are originally conceived to do handling operations and provide a large work space.

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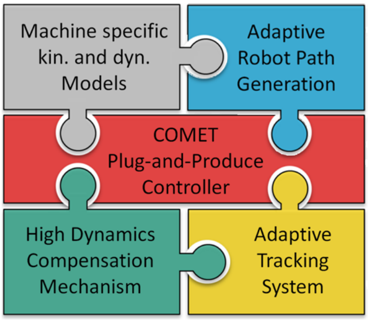

Fig. 1. Concept of accurate machining with industrial robot in COMET [2]

The traditional six rotational axes enable a big flexibility because of the vast set of positions and orientations which can be targeted. As this serial design of industrial robots enables several advantages on the same time the serial chain of joints is the major disadvantage of robots when trying to compete with machine tools. The errors of all joints sum up to the tool centre point (TCP) and reduce the precision of the robot. As soon as higher precision are needed robots are replaced by traditional machine tools. Therefore a much larger set of applications could be addressed by robots if the accuracy could be increased. One possible approach to increase robot precision is the precise description of the sources of error and their usage for compensations. This topic is dealt within the EU/FP7-project COMET [2].

The sources of error in robot machining are investigated and compensation mechanisms are set up in order to increase to accuracy in the machining process. The combination of different compensation approaches aim at a guaranteed accuracy of 50 µm. The target system is demonstrated in Fig. 1. Four steps are taken towards accurate robot machining: Model-based compensation is combined with a holistic programming approach. The additional tracking of the robot's TCP allows to feed the reference back to the robot controller and to an external high dynamic compensation mechanism compensating for the frequencies exceeding the bandwidth of the robot [3], [4]. This paper is organized as follows. Section 1 describes the relevance of robot machining and the impact of the achieved accuracy. A survey on sources of error is given in Section 2. Section 3 gives a detailed analysis of the characteristics of influences and provides dependencies. After presenting an overview over compensation strategies and evaluating the effects in Section 4 the paper finishes with conclusions and an outlook in Section 5.

2 Survey of Sources of Error in Robot Machining

Among the different performances related to the robot itself, precision is often used to describe its capabilities, and is further divided in: repeatability, accuracy and resolution. Repeatability and accuracy estimate the closeness between a set of attained positions and orientations of the TCP, when repeating the robot motions into the same commanded pose and their nominal values [5]. Resolution encompasses also programming resolution. Since industrial robots were designed to execute repeatable operations, their accuracy is lower than their repeatability. A typical industrial manipulator accuracy is about ±1 mm [6], [7], but values of 0.3 mm could be reached with accurate compensation [8]. Repeatability ranges in 0.1 - 0.03 mm [9]. Errors are responsible for the degradation of these performances. In order to obtain a clarification of the sources, a first distinction can be carried out among sources of error in the robot itself (its mechanical structure, basement and control system) or robot dependent, sources external to the robot (cell and auxiliary devices) and process (or task) dependent sources.

2.1 Environment Dependent Errors

The real accuracy of a robot depends strongly on the full chain of components between the tool on the TCP and the floor. Starting from the environment the structure of the building has an impact on the behavior of the robot. The presence of a basement changes the transmission from the environment on the robot. Especially, when measuring in the range of µm those effects cannot be neglected. In Fig. 2 a typical situation for a production facility environment is considered, disturbances arising from a pallet truck and passing people are applied. The signals are the relative movement between the Keyence sensor, with an accuracy of 1 µm, and the robot which are both attached on the 14 tons machine bed. An FFT of the signals reveals the main resonances to be similar to the resonances of the robot. It can be concluded that the measured signal is a real movement of the robot due to disturbances from the environment.

The chain of transmission of disturbances continues with the material of the floor and the fixture of the robot to the floor. Due to the big lever from the base to the tool small deformations in the base lead to big deviations on the tool. Moreover, an influence which must not be neglected is temperature. Different materials with different coefficients are used within an industrial robot which leads to a deformation which is hard to predict [11]. Also the tool holder and spindle support compliance must be taken into account. In general their contributions to the compliance of the system cannot be neglected. Further, cell calibration is another important issue which directly effects the final quality achieved. In robotic machining, the cell environment replaces the machine tool basement and the fixturing feature of the latter should be replaced with dedicated devices. In modern robotic cells, offline robot programming methods are used when the robot tasks are complex, as in the case of robot path required for machining. The current practice of creating the robot path with the aid of CAD/CAM software [2] requires a close matching between the CAD representation of the workcell and its real environment. Current approaches are based on CAD knowledge of the cell, devices (e.g. tool holder) and robot, which provide extreme flexibility but impose to adopt further calibration strategies to fulfill process accuracy requirements. Following the common approach of cell calibration position and orientation of cell components are computed using vision-based automated algorithms [12], [13].

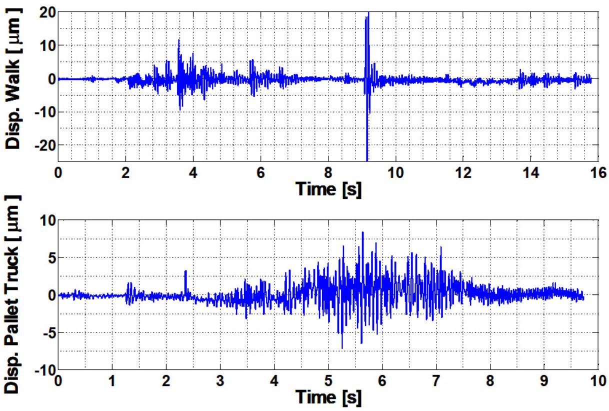

Fig. 2. Influence of disturbances measured on a 14 tons machinebed

2.2 Robot Dependent Errors

Within the mechanical robot structure two categories of errors can be distinguished: Geometrical errors and non-geometrical errors [8]. The former encompasses all the deviation due to imperfect geometries, mating or assembly errors, and these errors exist whether the robot is moving or not. The latter include all the sources related to the dynamical behavior of the robot. In addition, unlike the former, they are time-varying and change in magnitude during manipulator operations. The main effect of both of the sources is causing discrepancies between the real robot and its kinetostatic and dynamic model from which its characteristics are derived [14] and on which control is based [15].

a) Geometrical errors: Geometrical errors, which are generally compensated by calibration, arise from manufacturing or machining tolerances of robot components. Tolerances introduce variations in link geometry, as well as some variation in the orientation of the joints after link assembly and nonlinearities in the gears. Then, these errors will propagate to cause inaccuracy in the pose of the TCP. Links tolerances are not the unique source of geometrical errors. Joint errors in the axes are produced during the assembly of the various joint components due to clearance in motor and geared transmission mechanisms, backlash and bearing run-out errors. Backlash effects are a function of the geometrical looseness of the gears produced when they are mated together. These errors can make a significant contribution, even larger than that due to geometric tolerances, to robot positioning accuracy [16], [17]. Yet as in robot machining initially a cell calibration and a referencing procedure of the real position of the work piece are performed, only nonlinearities of the gears are considered in this paper. As the robot locally shows a rather good accuracy the impact of most geometrical errors (except nonlinearities of gears) can be reduced to errors in tool calibration (position of the tool on the TCP of the robot) and nonlinearities and measurement errors of the applied sensors. Yet these errors may vary depending on the individual circumstances as disturbances such as dust, conservation liquid and burrs of the workpiece may introduce additional errors.

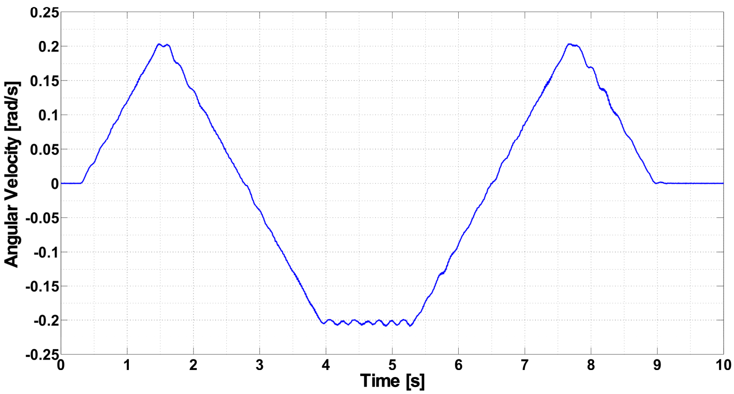

Fig. 3. Influence of compliance and backlash of axis 1

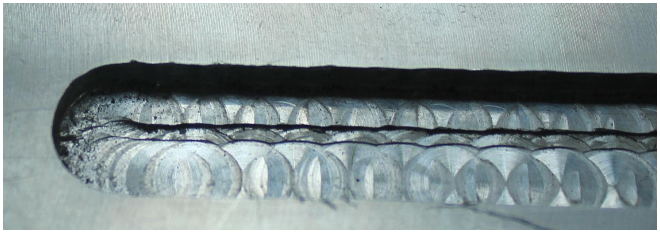

Fig. 4. Impact of gear backlash when machining in aluminium

b) Non-geometrical errors: Non-geometric errors also occur in a local environment and therefore cannot be compensated for by cell calibration. They arise from structural deformations of load-transmitting components, links and energy-transforming devices, wear and nonlinear effects such as nonlinear stiffness, stick-slip motion and hysteresis in servodrives [18], [19]. The compliance errors are due to the compliance of the links and joints under inertial and external load. In particular, joint compliance results from the torsional stiffness of the gearbox and the output drive shaft actuating the joint. Besides, the masses of the links cause an additional torque on the gears due to gravity effects. Especially during machining, forces add on the load of the gears and cause additional deflection. Link and joint compliance, causing the deflection of the links and finally the TCP, contribute up to 8-10% of the position and orientation errors of the TCP [8].

In addition, joint, and to a less extent links, compliance cause vibrations of the robot structure during its movements. Especially, when the industrial robot is driven with high speed, the industrial robot has large vibrations caused by the speed reduction mechanism [20]. Moreover, when the load on the TCP changes rapidly, or robot is undergoing fast movement, the resonant phenomenon will appear. Compliance and backlash are the two most effective influences of a robot's gears and drives. The natural damping of such systems is very low and yields to a slow decay characteristic of torsional oscillations [19], [21], [22]. In addition backlash yields too high torque impulses which can excite torsional vibrations. In Fig. 3 these effects of first axis measured on the TCP of a KR125 are demonstrated. Further measurements on the stiffness of joint 1 allowed the identification of its compliance as well as the identification of the backlash value. The results are: 0.9° for the backlash and $3.6 \cdot 10^6$ Nm/rad for the compliance. Machining experiments in aluminum show the great impact of backlash (see Fig. 4). The exemplary compliance of axis 1 is measured. The results are presented in Fig. 5. Assuming a lever of 1.5 m a realistic load on the TCP of 300 N caused by a machining process would result in a torque of 450 Nm and a deflection of 0.2 mm. In robotic machining process, the force induced deflection of the robot structure is the single most dominant source of error. Even though all components of an industrial robot contain intrinsic compliance, the major compliance can be assigned to the gears. Other important sources of error inside the mechanical structure are wear of the parts, the internal heat sources such as motors and bearings. Wear of the parts is strictly related to friction, in particular stiction, which in turn depends on temperature, joint applied torque and rotating speed [23].

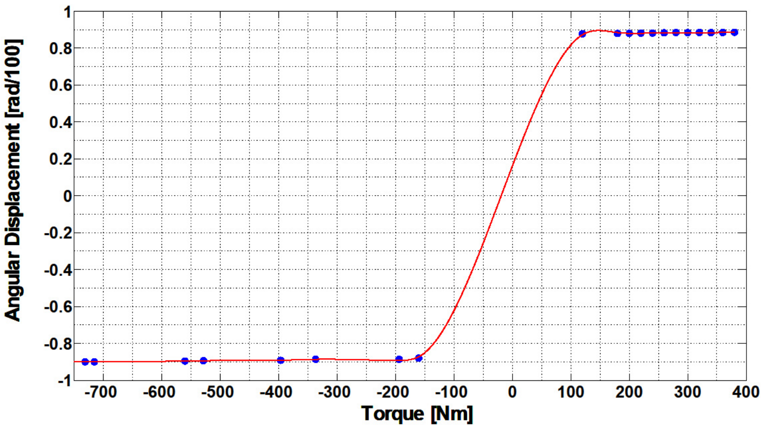

Fig. 5. Compliance measurements of axis 1 of a KR125

c) System Errors: Errors in this category include those caused by improper calibration, sensor measurement errors, control implementation errors and numerical round-off errors in the computer used for control. Sensor error is due to the joint angle sensor resolution and mounting. Due to the biggest lever axis 1 has the biggest impact on the TCP. When positioned in machining configuration minimal movements of 2 μm could be identified on the TCP. Control and algorithmic errors are related to the geometrical model implemented in the controller. Especially for model-based controls precise and accurate models of the nonlinearities are required [24]. Furthermore, also the controller sampling time contributes to these errors especially in a real-time context [25].

2.3 Process Dependent Errors

In machining applications the most important position source error is the machining force induced error. The machining force in an aluminum-milling process is hundreds of Newton, consequently the force induced error reaches values up to 1 mm [26] (compare Fig. 7 and Fig. 8). The structure of the robot transmits this force to the workpiece according to its mechanical characteristics. The values of the machining forces depend on the process parameters: spindle speed, axial depth-of-cut, radial depth-of-cut and chip load. They result in a specific value for the material removal rate value (MRR). In traditional machining application, feed is kept constant in spite of the variation of depth of cut and width of cut [27]. This will introduce a dramatic change of MRR, which would result in heavy changes in the machining force. The lubrication system is another important factor, especially for the final quality of the workpiece. The lubricating oil reduces the contact friction coefficient between the workpiece and the cutter, moreover this contributes to avoid the first type of chatter. The effects are measurable on the final quality surface of the machined part (e.g. roughness). Chatter is one of the major reasons preventing the adoption of robot for machining process [28]. At specific combinations of the foregoing parameters and due to thermo-mechanical effects on the chip formation (primary chatter) and regeneration of waviness of the surface of the workpiece caused by the vibration of the cutter (secondary chatter), the amplitude of cutting force increases and produces heavy vibrations on the robot and then on the TCP which interact with the workpiece [29]. As a result the surface of the workpiece becomes non-smooth.

3 Analysis of Errors in Robot Machining

Whereas the previous section explained the sources of error in robot machining in detail, this section aims at describing the resulting effects. The mapping of sources and effects allows then a final evaluation where the major errors in robot machining result from and which sources need to be addressed in order to improve quality when machining with industrial robots.

3.1 Experimental Setup

A KR125 from KUKA is used for the experiments (see Fig. 6). It is driven by a Beckhoff TwinCAT CNC and therefore optimized for the machining process. A Chopper 3300 spindle from Alfred Jaeger is used together with a 8 mm end mill tool with four teeth from Hoffmann Group. A Leica Absolute Tracker AT901 is used to measure the robot behavior and to determine parameters of the error sources. The tracker can perform three dimensional measurements at 1 kHz, with an error of $Err_{LT} < 20$ µm for the chosen area. A one-dimensional Keyence LK-G87 laser triangulation sensor is used in order to capture the influences of the surroundings on the robot. Robot and spindle are mounted on a 14 tons machine bed in order to decouple the cell from the surroundings. The lab is on first floor over the basement.

Fig. 6. Experimental setup with machine bed, KR125 robot, Chopper 3300 spindle, Keyence LK-G87 sensor and Lasertracker

3.2 Robot in Machining Operation

The robot in a machining operation is a complex system. The characteristic vibrations of the robot are combined with the oscillations due to the machining process. A machining example in ST-37 steel is chosen in order to demonstrate the typical effects in robot machining. The spindle speed is set to 10000 rpm and the feed is defined as 1000 mm/min. Using a tool with four teeth, the process parameters allow to evaluate the fundamental tooth passing (or first harmonic) frequency which value is f = 666.7 Hz. Machining is performed in full width cut. As the robot shows different properties when moving in different directions two experiments were performed:

- Machining a straight line following the y-axis
- Machining a straight line following the z-axis

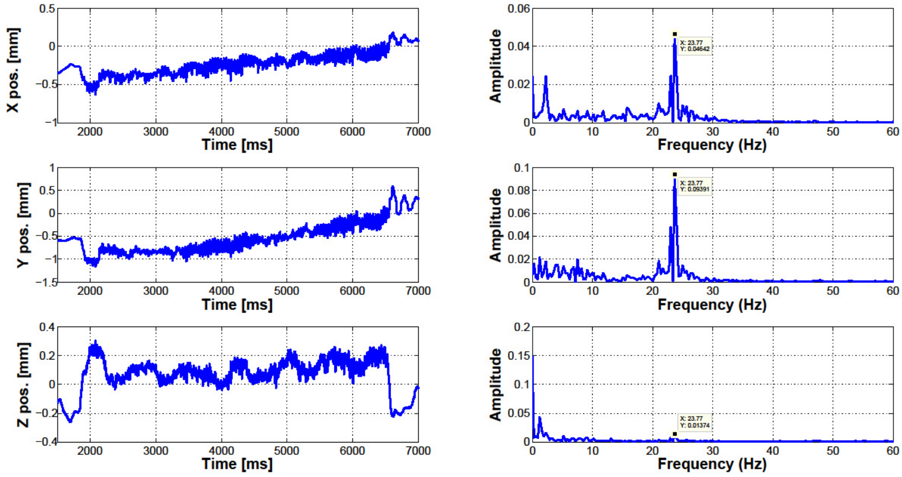

Fig. 7. Position and FFT when machining in y-direction

First of all the deflection of the robot when entering the material should be pointed out. In full width cut process forces are most present in feed direction and orthogonal to feed [30]. Due to the limited stiffness and these process forces the robot is deflected from its targeted path (Fig. 7 and Fig. 8). As the robot in the used configuration is much more compliant in z-direction than in y-direction the deflection orthogonal to path when machining in y direction is bigger. Secondly, the frequency analysis of the signal shows interesting results. As the attachment of the spindle is

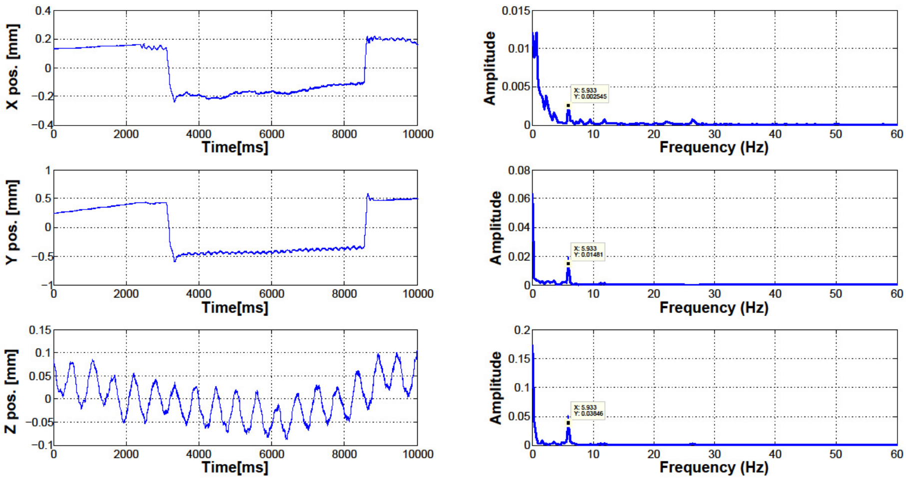

Fig. 8. Position and FFT when machining in z-direction

considered to be stiffer than the robot all lower frequencies can be assigned to the robot. It is obvious that the dominant frequency can be found at 5.93 Hz and 23.77 Hz. As the two machining scenarios cover the most compliant and the stiffest configuration of the robot it can be concluded that the bandwidth of the robot varies between these two values depending on its configuration. Finally also the nonlinearities of the gears are clearly visible with an amplitude of ±0.1 mm. They do no change with the speed of the robot but they show up as a low frequency in the FFT in the experiment. However, they do not limit the bandwidth of the robot but influence only the accuracy of the robot.

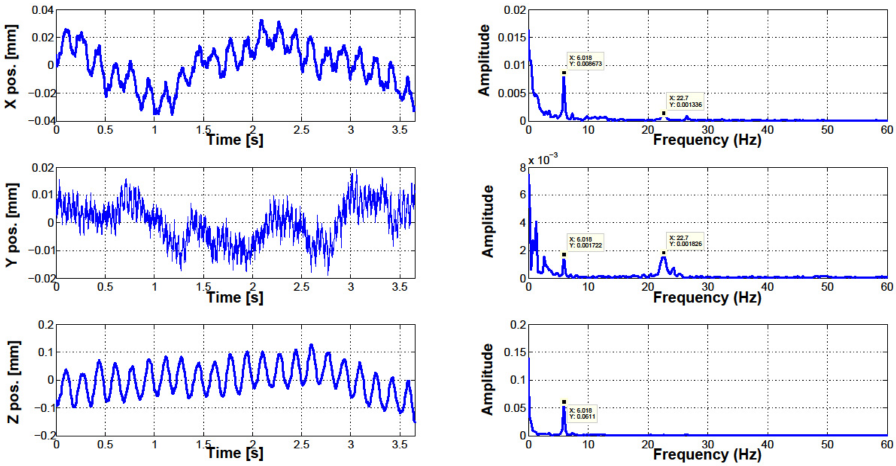

Fig. 9. Position and FFT when moving in z-direction

3.3 Robot in Free Space Motion

In contrast to a robot in machining a robot in free space movement is not excited by external disturbances. When moving the TCP in z-direction the impact of compliance and backlash of all axes result in the characteristic eigenfrequencies already experienced in machining (compare Section 3). Fig. 9 shows position and frequency properties of the free space motion. It should be noted that not only frequencies but also amplitudes of the oscillations in machining and in free space motion are comparable. As expected the nonlinearities of the gears appear like in the machining experiment.

4 Summary

According to the previous sections it can be concluded that the dominant frequencies in robot machining only depend on the mechanical properties of the robot. The effects can be traced back to the compliance and the backlash of the gears determining the frequency of position disturbances in the TCP. The results of all measurements describing the effects on the TCP are summarized in Table I. As expected, changing the configuration of the robot leads to different proprieties in terms of compliance and natural frequencies. This can be easily recognized in the final surface finishing (compare Fig. 4).

As in machining the exciting frequencies are always higher than the eigenfrequencies of the robot (compare section 3.2) the robot is very likely to oscillate with its eigenfrequencies. This mechanical constraint can only be influenced by mechanical modifications or overcome by external actuation like it is presented in [3], [4].

Table 1. Summary of effects in robot machining

Experiment	Deviation	Dominant frequency
Static displacement when machining in y	0.200 mm	-
Static displacement when machining in z	1.000 mm	-
Static displacement when moving freely in z	-	-
Dynamics when machining y	±0.250 mm	23.77 Hz
Dynamics when machining z	±0.050 mm	5.93 Hz
Dynamics when moving freely in z	±0.070 mm	6.02 Hz
Nonlinearities of gears when moving freely in z	±0.100 mm	-
Walking person passing	±0.020 mm	-
Pallet truck passing	±0.007 mm	-

5 Conclusion

The presented paper analyses the relevant sources of error when machining with industrial robots. The full mechanical chain from the environment to the flange including the robot controller was considered. The most important sources were identified and quantified. Experiments in machining and experiments in free space motion show that compliance and backlash are the most dominant sources. However when trying to achieve an accuracy of < 100 µm also the disturbances from the environment and errors from cell calibration need to be taken into account. Position and frequency analysis demonstrate the dependency on the robot configuration and identify the stiffest configuration of the robot. Based on the analysis a compensation of compliance and backlash can be identified as being most effective. Calibration of the robot kinematics and the calibration of the workcell can improve positioning accuracy and results also in better precision in machining. Proper decoupling of the cell components from the environment and from each other can reduce process disturbances further. The intrinsic oscillation of a serial robotic system can only be eliminated by external devices.

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