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Integrated approach to robotic machining with macro/micro-actuation

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ABSTRACT

A novel integrated approach to high-accuracy machining with industrial robots is presented in this paper. By combining a conventional industrial robot with an external compensation mechanism, a significantly higher bandwidth of the control of the relative position between the tool and the workpiece can be achieved. A model-based feedback controller for the compensation mechanism, as well as a mid-ranging control architecture for the combined system with the robot and the compensation mechanism are developed. The system performance is evaluated in extensive machining experiments, and the workpiece accuracies achieved are quantified and compared to the corresponding results obtained with state-of-the-art approaches to robotic machining. It is shown that the proposed approach to machining offers significantly higher accuracy, up to eight times improvement for milling in steel, where the required process forces, and thus the exhibited position deviations of the robot, are significant.

1. Introduction

During the last few decades, industrial robots have become an essential part of modern production and manufacturing. Traditionally, robots have been used for non-contact operations, such as handling and welding. Only approximately 0.6% of the industrial robots operational in the world are used for machining applications [1]. Such applications include milling and grinding, which require contact between the manipulator and the machining tool or workpiece. Milling is usually performed using dedicated machine tools, such as computer numerical control (CNC) machines, because of their high positioning accuracy and stiffness. Considering that industrial robots may offer flexible and cost-efficient machining solutions, the interest for robotic machining has increased. The challenges to overcome are to achieve acceptable accuracy of the machined parts and enable manufacturing based on computer-aided design (CAD) specifications, despite nonlinear dynamics in the robot joints and the comparably low structural stiffness affecting the achievable end-effector position accuracy [2,3].

In this paper, an integrated approach to robotic machining is presented, which utilizes macro/micro-actuation with a conventional robot and an external piezo-actuated 3D compensation mechanism [4,5]. We presented a model-based solution for the tool position control with a prototype version of the compensation mechanism in [6,7] and a subsequent refinement in [8], where the nonlinear dynamics of the piezo-actuators were in focus. The control strategy proposed in these papers is here extended and applied to a new compensation mechanism with an improved mechanical design, as presented in [9]. In addition, a mid-ranging control strategy is designed for the integrated macro/micro-manipulator control, and subsequently implemented. The complete control architecture and robot cell are evaluated using an experimental setup.

1.1. Background

Motion control for industrial robots has been studied for several decades and the development has thus reached a mature level [10,11]. The joints of the robot are typically position-controlled, while the Cartesian end-effector position and orientation are estimated based on the forward kinematic relations, *i.e.*, no explicit workspace sensing is used. While certain methods and commercial products offered by robot manufacturers exist for

Abbreviations: ADC, analog to digital converter; CAD, computer-aided design; CAM, computer-aided manufacturing; CMM, coordinate measuring machine; CNC, computer numerical control; DAC, digital to analog converter; ILC, iterative learning control; IMC, internal model control; LED, light-emitting diode; LQG, linear-quadratic Gaussian; PLC, programmable logic controller; PID, proportional-integral-derivative; SIMO, single-input multiple-output; VPC, valve position control

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achieving very high position accuracy for movement of the robot end-effector in free space or under constant load, no complete approach has been proposed to achieve this in the presence of dynamic process forces affecting the end-effector. Insufficient position accuracy in machining with industrial robots is a well-known problem in manufacturing; an experimental investigation was presented in [12]. The accuracy tolerances in manufacturing processes are usually in the range of ± 100 μm or lower [13]. This can typically not be achieved using a conventional industrial robot in application scenarios where strong process forces are required to execute the desired task.

The fundamental problem of insufficient position accuracy of the robot in the presence of process forces is nonlinear joint dynamics, such as backlash, friction, and nonlinear stiffness of the gear box [14–16]. These nonlinear dynamics significantly degrade the end-effector position accuracy of the robot, and consequently, the accuracy of the machined parts. The feedback control of the robot joint-positions is typically based on sensor data from the motor side of the gear box, whereas the primary interest in applications is the arm-side positions, since they represent the actual workspace position, if link flexibilities are neglected.

1.1.1. State-of-the-art

Previous approaches to increasing the position accuracy in robotic machining are primarily based on kinematic calibration [17–19] and stiffness modeling of the manipulator [2,3,20–23]. In the kinematic calibration procedure, the kinematic parameters of the robot—*e.g.*, the Denavit–Hartenberg parametrization [24]—are determined with high accuracy using optical measurement systems for a constant load attached to the robot end-effector. In stiffness compensation methods, the manipulator stiffness matrix, in joint space or in operational space, is determined offline based on experimental data and a subsequent online position compensation is performed based on the measured process forces. These methods do, however, suffer from configuration-dependent stiffness (to some extent handled by joint-based stiffness models) and the necessity of accurate stiffness models. In addition, end-effector force sensor data are necessary both in the comparably extensive measurement and modeling phase and when executing the machining task.

Other approaches to increasing the position accuracy in robotic machining processes are based on sensor data from high-precision 3D or 6D position measurement sensors [25–27], also referred to as coordinate measuring machines (CMM). The sensors can be used to provide end-effector position feedback for online corrections. The main limitation of these methods is the disturbance rejection bandwidth at the end-effector of the robot manipulator, but also communication delays for sensor data and noise in the measurements influence the achievable performance. As a result of the cutting process, high-frequency disturbances on the robot end-effector position are to be expected, and therefore a high-bandwidth position control of the robot is essential in order to achieve sufficient accuracy of the machined parts.

Another set of methods proposed for increasing the accuracy of industrial manipulators is based on iterative learning control (ILC) [28–30]. Using arm-side position sensors and dynamic models, the accuracy of repetitive robot motions could be increased iteratively. It is to be noted that some of these methods were applied offline, and required an initial experiment to be performed, such that relevant sensor data can be collected for the subsequent compensations. However, also online approaches to ILC have been proposed, see, *e.g.*, [31]. Further, previous applications of ILC in robotics described in the literature primarily considered the case when the end-effector was moving in free space. This is not applicable in machining, where the required process forces are the dominant source of position errors.

In contrast to the approaches described in the previous paragraphs, the strategy proposed in this paper comprises workspace sensing using 6D position sensors, combined with macro/micro-actuation. The concepts of macro- and micro-actuators were introduced in [32,33], together with a control architecture for increased bandwidth of the end-effector position control. The macro-actuator has a large workspace, but has a limited position-control bandwidth. Typical values for the bandwidth of the end-effector position control for industrial manipulators are in the range of 10–30 Hz, depending on the configuration [12]. In contrast, the micro-manipulator has significantly higher bandwidth, but a geometrically limited workspace. Hence, the micro-manipulator is to compensate for the high-frequency position deviations that occur during milling, which the macro-manipulator *per se* is unable to compensate for because of its limited disturbance rejection bandwidth at the end-effector. The notions of macro- and micro-actuation and manipulators have been adopted in this paper.

Piezo-actuated mechanisms based on flexure elements have been proposed for nano manipulation earlier, *e.g.*, [34,35]. Although the compensation mechanism considered here utilizes similar components in its mechanical design, there are significant differences. Previous designs were designed for compensation in micro- and nano-manipulation, whereas the micro-manipulator considered in this paper is designed for machining processes with industrial robots, where strong process forces are required to fulfill the specified task.

1.2. Problem formulation

The objective of this research is to develop a complete robot cell setup and an accompanying integrated control architecture, to the purpose of high-accuracy robotic machining. The robot cell design, as well as the required hardware for controller execution and communication channels, should be defined and experimentally verified. The control design is based on dynamic models of the systems involved. In addition, to demonstrate the effectiveness of the proposed approach to machining in industrially relevant machining scenarios, milling experiments in steel should be performed and the results are subsequently quantified and compared to machining results obtained using state-of-the-art approaches. The goal in terms of machining accuracy is to reach a maximum error within ± 100 μm, which should be obtained for stiff materials such as steel, where the required process forces are significantly stronger compared to, *e.g.*, aluminum. The long-term goal of the research presented in this paper is to enable manufacturing with industrial robots, based on CAD specifications, achieving machine-tool accuracy of the produced parts.

1.3. Outline

This paper is organized as follows: The robot cell, system setup, and the communication interfaces are described in Section 2. Subsequently, Section 3 presents the developed model-based controller for the micro-manipulator and the control architecture for the integrated macro- and micro-manipulator systems. Further, in Section 4 the modeling results are presented. In addition, results obtained from milling experiments in steel, with and without online position compensation with the macro/micro-actuator setup, are presented and evaluated. The significance of the obtained results is discussed, and based on CMM measurements of the workpiece geometries and surface-roughness measurements, the proposed method to machining is contrasted to state-of-the-art methods in Section 5. Finally, the paper is summarized and conclusions are drawn in Section 6.