Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-12 (2016) 011–016

Model Predictive Feed Rate Control for a Milling Machine

S. Stemmler * D. Abel * O. Adams ** F. Klocke **

* Institute of Automatic Control, RWTH Aachen University, Germany, 52056 Aachen (e-mail: S.Stemmler@ irt.rwth-aachen.de).
** Laboratory for Machine Tool and Production Engineering, RWTH Aachen University, Germany, 52056 Aachen (e-mail: O.Adams@wzl.rwth-aachen.de)

Abstract: Deep process and machine knowledge is necessary for setting up conventional manufacturing systems. Hence, the degree of automation shall be increased to ensure high productivity and flexibility. An essential element of this goal is the systematic establishment of additional control loops, e. g. in form of machine-oriented control loops or higher process control loops. In the following a method is presented to decouple higher process control loops from machine-oriented control loops. For this a Model-based Predictive Controller (MPC) is used to predict future machine behavior. Based on this prediction the MPC adapts the reference from higher process control loops with respect to machine dynamics and time delay of machine as well as controller computing delays and communication delays. Thereby constraints can be defined to fulfill requirements that are important for the control task or that are given by the higher control loops. This approach is applied to a milling process.
First the machine behavior is identified and a machine model with time delay is introduced. Then a Kalman Filter for estimating unknown states and a MPC are designed. An example is presented, where the process force is controlled in order to fulfill a higher objective, e. g. minimum production time. For this case it is shown, that the given method ensures desired process and machine limits with respect to given machine dynamics and time delays. Consequently the presented concept is usable for transferring higher process optimizations to other similar machine types without adaptions in higher process control loops. Only the MPC-based interlayer must be adapted, with respect to machine model and required constraints.

Keywords: Model-based control, Predictive Control, Closed-loop identification, Milling, Manufacturing systems, Production systems, Self-optimizing systems

1. INTRODUCTION

Today's manufacturing systems are characterized by their high number of adjustable parameters and settings. These numerous settings give the opportunity to optimize the process in wide range. If these machines are adjusted for the desired product, the machines are characterized by their high productivity. Therefore many preparation steps are necessary to reach optimal machine settings. The first step is the definition of functional and economical product requirements, which are often given by the customers. Considering the product requirements the machine operator sets up the machine. If the product is known and was manufactured in the past, the machine operator can often use well-known machine settings. Also the usage of technology tables supports the machine operator, if these technology tables are available for the demanded product. If the demanded product is new without similarities to previous manufactured products, technology tables and optimal machine settings must be determined empirically by experiments. Consequently, many samples must be manufactured until the desired product specifications (e. g. quality, dimensional accuracy) are reached. During this time no products are manufactured, which can be sold to the customer.

The time of the machine adjustments greatly depends on experiences of machine operator. But in all cases the setting time is a great economic loss. To decrease this effect, manufacturing systems of the future shall automatically adjust to fluctuating requirements. Therefore an essential element is the systematic establishment of additional control loops. Additional to machine-oriented control loops, it is necessary to establish process control loops, which keep the process within predefined boundaries. These control loops can be quality control loops as well as other optimizations, which adjust process values and parameters depending on desired requirements, like manufacturing time, energy and material consumption. The concept of model-based self-optimization (see Permin et al. (2015), Brecher (2012)) is an approach for tackling this challenge. It is researched within the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" at RWTH Aachen University. The concept of model-based self-optimization uses machine-oriented control loops and adds higher optimization loops in order to control higher objectives, e. g. quality, dimensional accu-

10.1016/j.ifacol.2016.07.542

racy and manufacturing time, that are partial contrary. Thereby the general control structure is separated into two parts, the model-based optimization system (MO-system) and the information-processing-sensor-actuator system (ISA-system). Thereby the ISA-system consist the machine-oriented control loops, which are computed at high frequency to gain reproducibility of machine values. In contrast, the MO-System considers overall process optimization loops, which are computed at lower frequency due to complex process models. These overall process optimization loops estimate the present operation point and compute an optimal operation point with respect to the higher objectives. This concept is applied to several processes, e. g. injection molding, milling and others (see Hopmann et al. (2015), Klocke et al. (2013), Brecher and Wesch-Potente (2014))

In the following a concept is described, that decouples machine-oriented control loops from higher process control loops (see Figure 1). Based on a Model-based Predictive Controller (MPC) an interface is introduced, that brings forward the opportunity to transfer higher process control loops to other similar manufacturing machine types, e. g. machines of different manufacturers for the same manufacturing process, without numerous adjustments. This method will be described for a milling process.

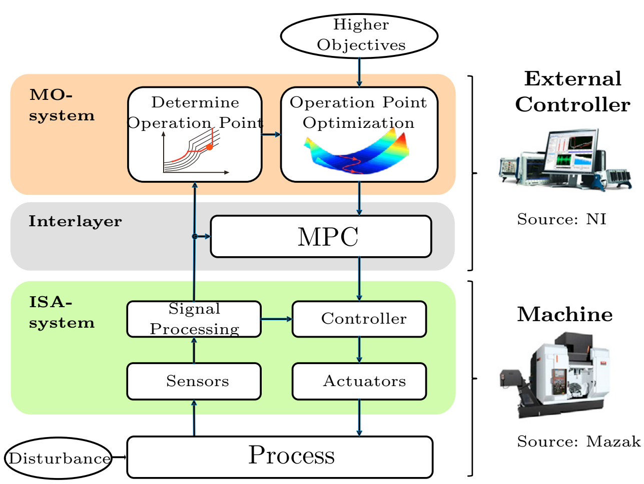

Fig. 1. Scheme of Model-based Self-Optimization with MPC-based interlayer

2. CONTROL IN MILLING PROCESSES

Milling is one of the most flexible metal cutting processes, as complex shaped work pieces can be produced using simple tool geometries. Today, multi-functional machining centers with up to five CNC-controlled axis are used in all industries for the manufacturing of complex free-form geometries. Depending on the machine's kinematics, most often three linear axis are realized on the tool side and two additional rotary axes are arranged on the table side, where the work piece is mounted. The desired work piece geometry is created, taking off work piece material with the rotating cutting tool. After planning the tool path in the computer aided manufacturing (CAM) software, the right selection of the process values feed velocity and cutting speed is essential for the part's quality. Process optimization e.g. increasing quality and decreasing manufacturing time, is achieved most often due to an a-priori optimization of the process values and parameters. Due to a missing feedback from the real manufacturing process, influences such as a variation of the work piece material or tool wear cannot be included. Online process control for an advanced optimization is not commonly used in industry. Considering the process forces, an accurate control system would be able to protect the tool and the machining center, control the resulting part geometry and reduce manufacturing time due to maximized feed velocities meeting the aforementioned opposed objectives. Beside expensive measurement systems, one reason for the small number of process force control systems in industry is the lack of easy-to-operate and adaptive control strategies. Standard controllers i.e. PI- or PID-controller have to be adjusted carefully, because the control path's transmission behavior usually shows a time delay affected behavior. Furthermore, the static gain changes with the geometric cutting conditions. Considering rather low feed rates and fast reacting control paths, a good quality of control is achievable with an adaptive PI controller, Nolzen and Isermann (1995). Fast changing geometric conditions result in high peak values of the process force, due to the changing control path gain. Including the knowledge of the machines general transmission behavior, Altintas describes a force control system using adaptive generalized predictive control, Altintas (2012). Therefore, the transfer function of the machine tool and cutting process is described as

$$G_c\left(z^{-1}\right) = \frac{F_p\left(k\right)}{f_c\left(k\right)} = z^{-1} \cdot \frac{B\left(z^{-1}\right)}{A\left(z^{-1}\right)}. \tag{1}$$

The variable f_c represents the feed velocity, which is applied to the machine tool, F_p is the resulting process force. The parameters A and B of the machine behavior are estimated online using a least squares algorithm. The generalized predictive control takes past, present and future values of the feed velocity and the cutting force into account. Hence, the achieved quality of control is higher compared to the quality achieved with simple standard control systems. Nevertheless, abrupt changing cutting conditions may result in high peak forces. In order to improve the quality of control, additional research on a model predictive control system for milling processes was carried out. In the following a model predictive control system for controlling process forces in milling is introduced, using optimized and process-specific reference trajectories. Controlling the process forces, using the feed velocity as manipulated variable, guarantees a high productivity of the manufacturing process, including a protection of the tool and the machining center. Therefore the machining center is equipped with a piezoelectric multicomponent force dynamometer to measure the process forces m_p. This allows highly dynamic measuring of process forces. Due to direct dependencies between controlled process forces q and controlled feed rate y, the process force q can be controlled by manipulating the feed rate y. Hence, an interface was developed by the machine manufacturer, which gives an input u for an external feed rate override. Based on this override the milling machine can be controlled by higher control loops, as it is depicted generally in Figure 2. In this case the objective is minimizing manufacturing time. Accordingly the optimization task is predicting process forces with respect to measured forces m_p, geometry