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Development of a CAM-in-the-Loop System for Cutting Parameter Optimization using an Instrumented Tool Holder

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Abstract

This paper presents a methodology for cutting parameter optimization based on integrating a Computer-Aided Manufacturing (CAM) system and an instrumented tool holder capable of identifying unstable process conditions during milling. Compared to state-of-the-art adaptive process control systems with feed rate and spindle speed override modification, the presented approach utilizes high-level CAM objects in the data loop, thus, provides opportunities for automatic adaption of the original machining strategy and various cutting parameters. Based on the presented CAM-in-the-loop approach, the system uses sensor feedback while producing the first piece to optimize the CAM planning parameters for all subsequent units of a specific production order. The approach is demonstrated using milling use-cases manufactured on a machining center with an instrumented tool holder for process vibration measurements.

Keywords: Closed-Loop; Milling; CAD/CAM; Chatter; NC-Code Optimization

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1. Introduction

Academia and industry have been researching chatter vibrations and their relation to cutting parameters for many years. Incorrectly chosen cutting parameters excite the machining system in its resonance frequencies, leading to unstable process conditions often resulting in poor surface quality of the machined workpiece. [1] Computer-Aided Design and Manufacturing (CAD/CAM) programmers usually rely on their experience for choosing a machining strategy and cutting parameters that avoid chattering in order to reach certain surface qualities. In practice, these selected parameters need to be tested at the machine by the Computer Numerical Control (CNC) operator, who performs a series of cutting tests adapting the original parameters to ensure all part quality requirements are met. This iterative optimization process between the CAD/CAM programmer and the CNC operator is time-consuming, costly, and blocks valuable machining time on the machine tool. In order to make this optimization process more efficient, different approaches and systems have been developed in recent years.

2. Related Work

Extensive research has been conducted on online chatter detection and suppression (Adaptive Process Control) as well as offline chatter prediction models especially in the area of smart manufacturing for milling applications, with the general goal of improving surface quality. [22]

2.1. Adaptive Process Control in Milling

Adaptive process control systems target to adjust cutting parameters during machining, utilizing different sensors positioned in the machine tool and adding deterministic data communication interfaces to the numerical control. Different technologies have been industrialized in recent years.

In [4, 16] an adaptive process control technology based on an instrumented tool holder has been presented. As stated by Bleicher et al. [3, 13], the system utilizes a Micro Electro Mechanical System (MEMS) acceleration sensor which can be integrated in various standard tool holder concepts. Since the sensor is positioned in the tool holder, hence, close to the cutting zone, accurate and high-frequency data acquisition with a sampling rate of 9.5 kHz is possible. The data is digitized internally and transmitted to a transceiver unit via bluetooth low energy.

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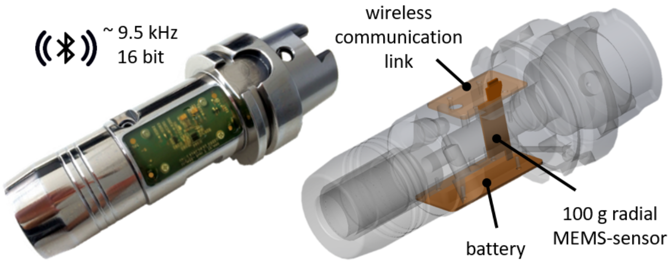

Fig. 1. Sensory Tool Holder System at TU Wien

A separate processing unit analyses the raw acceleration signals and identifies stable and unstable process conditions in real time using figures of merit. If unstable process conditions are detected, spindle speed and feed rate are adjusted on the numerical control based on pre-defined optimization strategies implemented on the processing unit. For communication between the system's processing unit and the numerical control, digital or analogue real-time communication can be implemented. An overview about the sensory tool holder is given in Fig. 1.

Examples of comparable approaches that integrate sensor systems close to the cutting zone in the tool (holder) can be found in [10] and [18]. Other industrialized systems such as Comara iCut [7] or Siemens Adaptive Process Control [17] focus on the utilization of spindle power sensors in the machine tool to adapt feed rate during machining in real time. The systems establish a closed-loop between the measurement system for spindle load and the numerical control, and increase feed rates if cutting conditions allow, and slow down if the process demands caution. By this, these systems can optimize cycle time, prevent tool breakage and reduce maintenance due to spindle load management. A similar system has been proposed by Ridwan et al. [15], presenting a fuzzy adaptive control used to keep a constant cutting load by adjusting feed rate during machining using feedback from spindle load sensors. ProMicron implemented an adaptive process control system utilizing a sensor for cutting force measurements in the tool holder and provides real-time feedback to the numerical control using Profibus interface [12].

2.2. *Integration of Machining Data in CAD/CAM*

Researchers also investigated methods for cutting parameter optimization by feeding machining data back into CAD/CAM environment. Armendia et al. [2] demonstrates an online collision avoidance system using actual and future (look-ahead) axis position data from the numerical control during machining. The future position data is evaluated in the virtual environment, and emergency stops are activated if collisions are calculated. Vitr [21] developed a human-assistance tool for manual optimization of machining strategy and cutting parameters by integrating numerical control data directly in a selected CAD/CAM environment. The selected data points from the numerical control can be visualized in addition to traditional Computer-Aided Manufacturing (CAM) machining data, supporting programmers in the optimization of their programs. Comparable work has been done by Plakhotnik et al. [11], where measured spindle power consumption has been integrated and visualized in a dexel-based material removal simulation, supporting manual optimization of cutting parameters. Mauthner et al. [9] combined data from the numerical control and measured vibration data from an external sensor integrated in a HSK tool holder. Moreover, automatic optimization of cutting parameter feedrate and spindle speed in the G-code files has been demonstrated. Ridwan and Xu [14] presented an overall architecture for smart machine condition monitoring. Building on the international STEP and STEP-NC standards, a new controller architecture has been developed, building an optimization platform for comprehensive cutting parameter optimization before, during and after the machining process.

2.3. *Virtual Optimization of Cutting Parameters in CAD/CAM*

In contrast to adaptive systems, which adapt provided cutting parameters during machining, various approaches are proposed for software supported, pre-machining optimization of cutting parameters in CAD/CAM simulation environments. Commercially available CAD/CAM systems provide the functionality to calculate average Material Removal Rates (MRR) and adapt feed rates for specific toolpath segments to maintain optimal and constant MRR [8]. Continuous research on improving the MRR segmentation algorithms in milling has been carried out [6]. An approach for simulating resulting surface roughness is demonstrated in [19]. [20] shows an exemplary commercial software tool for NC-Code optimization based on cutting force simulation.

2.4. *Summary of State-of-the-Art*

Past research has focused on various methods to support the optimization of cutting parameters and machining strategies to avoid unstable process conditions. On the one hand, progress has been made in the area of adaptive process control systems (online), capable to adapt parameters of the numerical control during machining in real-time. Presented work vary in the selection of the sensor type (e.g. acceleration, force, acoustic), the position of the sensor in the machining system (e.g. spindle housing, tool holder, cutting tool) and the selection of adaptable parameters on the numerical control (e.g. feed rate, spindle speed). On the other hand, work has been done in the area of virtual cutting parameter optimization (offline), using different methods such as modelling dynamic machining behaviour, integration of machining data from numerical control and other sensory equipment, as well as geometrical algorithms based on material removal rate simulation in CAD/CAM environments.

Nevertheless, current state-of-the-art systems demonstrate limitations for cutting parameter optimization since online and offline optimization techniques have been been investigated separately. Online systems such as the sensory tool holder, allow an real-time adaption of parameters during machining, however are usually limited to adapt feedrate and spindle speed override to interact with the machine tool. Changes in regards to toolpaths and machining strategies are not possible using cur-

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rent systems. At the same time, offline optimization tools in CAD/CAM environments are able to adapt a wider range of parameters, but are usually limited by modelling complexity and computation time, especially in the context of chatter limitation. The integration of described online and offline systems would combine advantages of real-time chatter detection and a full range of virtual parameter adaption in a CAD/CAM environment, thus, leading to a novel approach for ”self-learning” machine tools and automated process optimization.

3. Concept for CAM-in-the-Loop System

This paper presents a novel method for automatic cutting parameter optimization by defining a self-learning CAM-in-the-Loop machining system. In this work, state-of-the-art adaptive process control technology is used to identify unstable process conditions during milling, providing the CAD/CAM process planning software with the adjusted parameters and measurement data for automatic and sustainable parameter optimization.

3.1. System Architecture

The CAM-in-the-Loop concept builds fundamentally on a ”second time right” strategy presented in [9], proposing an adaption of cutting parameters directly in CAD/CAM and the generation of a new NC-Code after first-piece production, in order to run all subsequent parts with optimized parameters.

In the envisioned system, a CAD/CAM environment is responsible for providing respective machining strategies to manufacture a given workpiece geometry. In this step, machining operations, cutting tools, cutting parameters and the machining sequence is defined, cutter toolpaths are calculated and a machine executable G-code is generated. Due to the loss of information towards traditional G-codes in numerical controls [5], all relevant feature-related meta data (e.g. name of cutting operation) are exported to a separate industrial PC hosting a feature-based data collection application. During first-piece production using the generated NC-Code, an adaptive process control system monitors the cutting process, identifies stable and unstable cutting areas along the toolpath and adapts originally planned cutting parameters on the numerical control accordingly. At the same time, relevant process data created during machining by the numerical controller, the adaptive process control and the sensory systems is collected by the feature-based data collection application and linked to the original CAM meta data, establishing a data link which is otherwise lost during post-processing. Once the production of the workpiece is done, a rule-engine and/or machine learning algorithm analyses the linked CAM meta and process data, and evaluates potential optimization of cutting strategy and cutting parameters. If adaptions in the process plan are necessary, a direct interface towards the CAD/CAM environment enables an operation and manufacturing-feature specific optimization. Required toolpath simulations and post-processing steps can be triggered automatically, and optimized NC-codes are generated. The production of all subsequent parts can now utilize the optimized NC-code providing stable process conditions along the toolpath.

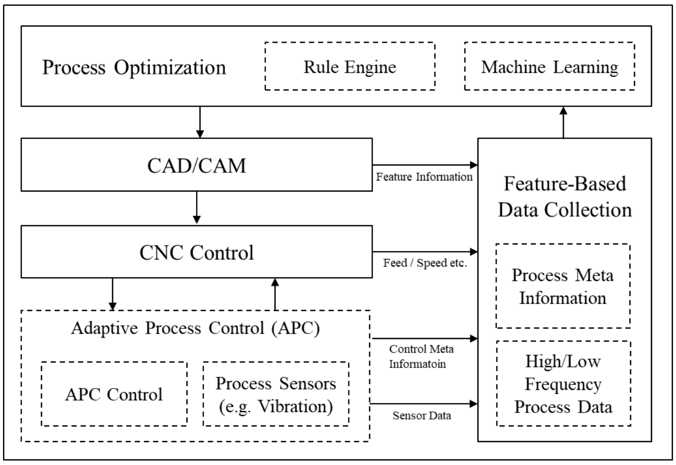

Fig. 2. CAM-in-the-Loop System Architecture

The described system supports the identification of optimal cutting parameters for new production parts by combining CAD/CAM process planning functionality with modern adaptive process control capabilities. Based on the feedback provided by the machining system, given process plans can be evaluated and adaptions on cutting strategy and parameters can be triggered. Since all changes are triggered in the CAD/CAM system, standard engineering processes can be utilized (e.g. documentation, simulation, post-processing). Overall, the entire process becomes more efficient, data-driven and more flexible since all CAD/CAM related adaptions of the process plan can be used for optimization. The envisioned concept is illustrated in Fig. 2.

3.2. Prototype Development

A prototype of the envisioned CAM-in-the-Loop system has been realized at TU Wien Pilotfabrik Industrie 4.0 in Vienna. The prototype targets to identify unstable process conditions during milling using a selected adaptive process control system and to automatically update cutting parameters in a given CAD/CAM process plan, based on the data feedback provided.

First, an exemplary adaptive process control system has been selected. In the context of this work, an instrumented tool holder system, developed by the Institute of Production Engineering and Photonic Technologies has been used. The system identifies unstable process conditions and adapts numerical control parameters feedrate and spindle speed override in real-time. Relevant sensor data as well as system configuration files can be accessed via OPC UA communication technology. The adaptive process control system has been implemented on a 5-Axis CNC machining center EMCO MaxMill500 with a Siemens Sinumerik 840d sl CNC control and can be de-/activated using defined machine commands (M-commands) in the respective G-code lines.

Second, Siemens NX CAD/CAM software has been set-up and the required machine tool kinematics and 3D models have

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been implemented in the system environment. In addition to standard CAD/CAM functionality, an open programming interface (NXOpen) is provided and can be used for data export/import, system automation (e.g. start of a post-processor run) or to create new graphical user interfaces to support additional communication with the user or external software systems. In the presented prototype, NXOpen has been used to import and export relevant process plan data (e.g. machining strategy, cutting parameters) using standard XML and CSV file format. For later mapping of the CAD/CAM process plan and the actual process data, adaptions in the standard Sinumerik post-processor have been implemented. Additionally, the external configuration of the adaptive process control system, has been integrated in Siemens NX environment, thus allowing operation and manufacturing-feature specific configuration and activation of the system for an individual workpiece process plan. Required adaptions of the post-processor to communicate with the numerical control and adaptive process control system have been implemented using Sinumerik specific user defined events.

Third, the proposed feature-based data collection application has been developed in python programming language and setup on an industrial EDGE computer, connected to the machine and sensor network. The application is responsible for gathering meta data from Siemens NX and linking relevant process data from the Sinumerik control as well as the sensory tool holder system during machining. Activation of the data collection functionality is triggered once the numerical control starts the NC-program and collects selected data points from the numerical control (e.g. actual feed, actual spindle speed, override values, axis position) and the sensory tool holder system using standard OPC UA and MQTT communication technology. Linking meta and process data is achieved by providing unique identifiers defined in the CAD/CAM environment in the G-code lines. The presented prototype uses the Sinumerik specific ”Message” command (”MSG”) to provide necessary context information during NC-Code execution. The application has been deployed on an industrial edge device, providing flexibility in case more than one machine tools are connected.

Fourth, all data points are analyzed using a rule-engine data script, identifying and evaluating need for CAD/CAM process plan adaptions. Due to the CAD/CAM contextualization during the data collection, all process information can be analyzed for individual machining operation, manufacturing-feature, cutting tool and cutting parameters. The script contains a set of pre-defined machining rules, that enable the system to propose operation and manufacturing-feature specific optimization of not only cutting parameters (e.g. spindle speed, feed rate) but also machining strategies and cutter toolpaths (e.g. cutting depth/width). This allows for a wider range of optimization algorithms and remove the limitation of state-of-the-art systems focusing on numerical control parameters only. Proposed adaptions of original process plans are executed via NXOpen interface including update of respective strategies and parameters, toolpath simulation and a new post-processor run. The hereby created, optimized NC-code can now be used as a standard process for all subsequent production parts.

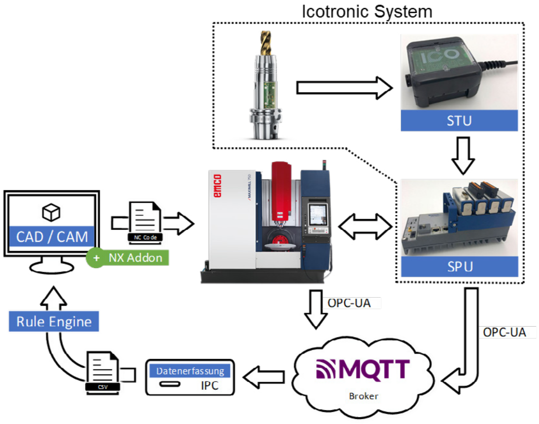

Fig. 3. Implemented Prototype at TU Wien Pilotfabrik Industrie 4.0

In Fig. 3 the implemented prototype at TU Wien Pilotfabrik Industrie 4.0 is depicted.

4. Proof of Concept

To demonstrate the feasibility of the proposed approach, the described prototype has been tested in various cutting experiments at TU Wien Pilotfabrik Industrie 4.0.

For the experimental setup, the prototype has been implemented on the described 5-axis CNC machining center EMCO MaxMill500 with a Siemens Sinumerik 840d sl CNC control. To simulate unstable process conditions, thus, to trigger the adaptive process control functionalities of the sensory tool holder system, a rectangle aluminum workpiece (EN AW 6060, L x W x H: 133x65x50 mm) with a pre-machined step-feature (H: 10 mm) in center has been used. The workpiece is cut in negative X-direction (ae = 4 mm, ap = 11 mm, feed rate = 1000 mm/min, spindle speed 10600 rpm) and resulting cutting vibrations (IFT-Value) are measured. Once reaching the pre-machined step-feature in the center of the workpiece, cutting vibrations increase and exceed experimentally pre-defined vibration limits from the configuration loaded in the processing unit, thus, triggering the adaptive process control features of the sensory tool holder system. The system is capable to gradually reduce feed rate and/or spindle speed overrides on the numerical control until measured vibration values fall again below the defined limits and stable process conditions are indicated. In the presented experiment, stable process conditions have been detected at a new feed rate of 480 mm/min. During this process, all parameter changes are logged in the described prototype and used for data analysis. In the presented proof-of-concept, a simple optimization algorithm has been implemented, considering the lowest feed rate and spindle speed measured during an adaptive machining process, as the new optimized planning values for the respective CAD/CAM operation. After running the automated adaption in the system, a new feed rate of 480 mm/min has been applied, and a new NC-Code is generated. A second cut with the new feedrate is executed, resulting in significantly lower process vibrations along the cut. Fig. 4 illustrates the measured feed rate and spindle speed from the numerical con-

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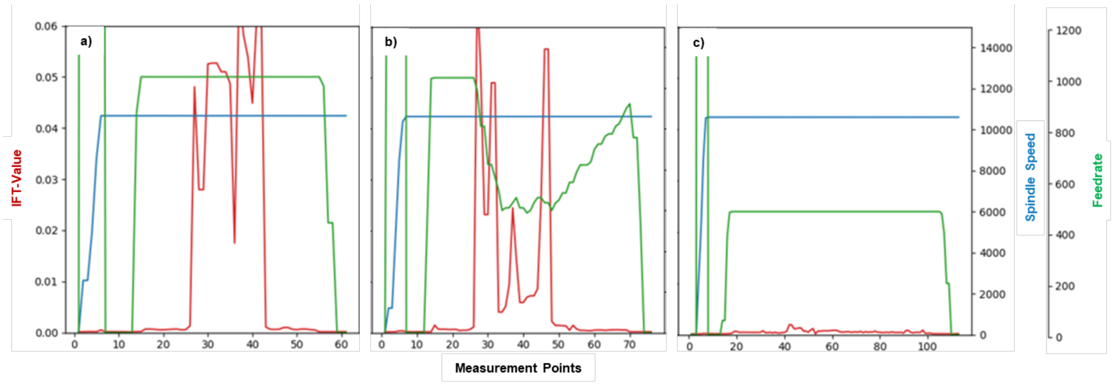

Fig. 4. Prototype Testing: (a) Original NC-Code - APC not active; (b) Original NC-Code - APC active; (c) Optimized NC-Code - APC not active

trol as well as the vibration value from the sensory tool holder (IFT-Value) for three test cuts: (a) cutting without adaptive process control and original cutting parameters, (b) cutting with adaptive process control active and original cutting parameters, (c) cutting without adaptive process control and updated feedrate of 480 mm/min. identified during cut (b).

A second experiment to test the developed prototype was executed on a DMGMori DMU75 monoblock 5-axis CNC machining center with a FANUC FS31IB5 numerical control. Due to the different control as well as a different version of the sensory tool holder system, slight adaptions in the developed interfaces were necessary, however, supported by the flexible architecture of the prototype. The experiment investigates the applicability of the proposed system in a more realistic setup of real chatter occurrence without pre-machined step-features. A rectangle aluminum workpiece (EN AW 6060, L x W x H: 120x30x80) is cut in negative direction (ae = 5 mm, ap = 10 mm, feed rate = 1000 mm/min, spindle speed = 4400 rpm). During the first cut with original cutting parameters, high vibrations occurred, exceeding the pre-configured vibration limits and the adaptive process control unit reduced spindle speed override until stable process conditions could be detected at 4220 rpm. Similar to the first experiment, the lowest spindle speed measured at stable process conditions is considered as new planning value and is updated in the CAD/CAM machining operation accordingly. A second cut with updated spindle speed and deactivated adaptive process control unit provided significant lower cutting vibrations (IFT-Value) and a visibly improved surface roughness. Additionally, since only spindle speed has been adapted, the optimization has no negative impact on material removal rate compared to the original process plan. Fig. 5 shows the cutting toolpath in CAD/CAM environment with the measured vibration data as well as the machined part surfaces with original and optimized NC-Code.

5. Conclusion and Future Work

Modern sensor equipment and adaptive process control systems provide detailed feedback about the machining process and allow real-time adaptions of specific cutting parameters. While implemented systems vary in terms of sensor and communication technologies, all state-of-the-art approaches show limitations as they adapt parameters in real-time on numerical control level, however do not take comprehensive CAD/CAM process planning environments into account. Hence, systems are capable to react on unstable process conditions but are not designed to learn from previous mistakes for future part programming. This paper presents a novel method and an industrial-relevant approach for effective and automated optimization of machining strategies and cutting parameter, by integrating adaptive process control systems and CAD/CAM process planning environments. A prototype of the envisioned system was implemented at TU Wien Pilotfabrik Industrie 4.0 in Vienna and has been validated using different demonstration scenarios. Firstly, the designed system architecture supports an industrial oriented approach for contextualized data collection, combining CAD/CAM process meta information, actual machining data from the numerical control and sensor data from an instrumented tool holder. Secondly, the integration of CAD/CAM environment in the optimization loop demonstrates new opportunities for process optimization by adapting not only cutting parameters, available on numerical control, but also CAD/CAM owned machining strategies and cutter toolpaths. Thirdly, a demonstrator for an industrial relevant application scenario has been established, highlighting opportunities towards an automated parameter optimization loop after first-piece production of a new part geometry. Further research is required to investigate industrial application of the proposed CAM-in-the-Loop approach for more complex part geometries and machining processes. Furthermore, intensive work is needed to develop detailed optimization rules, considering not only process data and cutting parameters, but also machining strategy, tool wear, expected surface roughness, machine tool dynamic behaviour (e.g. stability lobes) and other relevant criteria. For example, different ramp in/out or roughing/finishing strategies could be integrated in the system environment. Additionally, various machine learning approaches such as artificial neural networks, regression algorithms or response surface methods could be investigated in the context of the proposed CAM-in-the-Loop approach.

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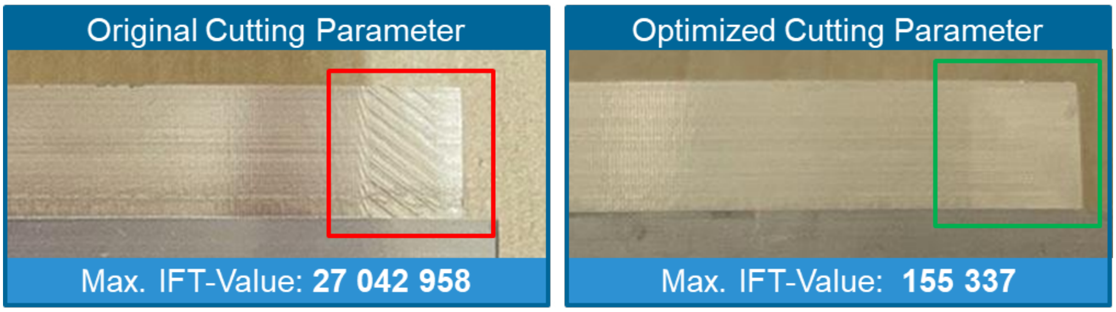

Fig. 5. Part Surface with Original and Optimized Cutting Parameters

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References

[1] Altintaş, Y., Budak, E., 1995. Analytical prediction of stability lobes in milling. CIRP Annals 44, 357–362. URL: https://www.sciencedirect.com/science/article/pii/S0007850607623427, doi:https://doi.org/10.1016/S0007-8506(07)62342-7.

[2] Armendia, M., Fuertjes, T., Plakhotnik, D., Sossenheimer, J., Flum, D., 2019. Cyber-Physical System to Improve Machining Process Performance. Springer International Publishing, Cham. pp. 197–208. URL: https://doi.org/10.1007/978-3-030-02203-7_12, doi:10.1007/978-3-030-02203-7_12.

[3] Bleicher, F., Ramsauer, C.M., Oswald, R., Leder, N., Schoerghofer, P., 2020. Method for determining edge chipping in milling based on tool holder vibration measurements. CIRP Annals 69, 101–104. URL: https://www.sciencedirect.com/science/article/pii/S0007850620301220, doi:https://doi.org/10.1016/j.cirp.2020.04.100.

[4] Bleicher, F., Schörghofer, P., Habersohn, C., 2018. In-process control with a sensory tool holder to avoid chatter. Journal of Machine Engineering .

[5] Brecher, C., Vitr, M., Wolf, J., 2006. Closed-loop capp/cam/cnc process chain based on step and step-nc inspection tasks. Int. J. Computer Integrated Manufacturing 19, 570–580. doi:10.1080/09511920600622064.

[6] Chan, K.C., Wang, C.C.L., 2015. Progressive segmentation for mrr-based feed-rate optimization in cnc machining, in: 2015 IEEE International Conference on Automation Science and Engineering (CASE), pp. 691–696. doi:10.1109/CoASE.2015.7294160.

[7] Comara GmbH, 2021. Regulate feed automatically. Website. https://www.comara.de/en/icut/ (last downloaded 2021-12-03).

[8] Kurt, M., Bagci, E., 2011. Feedrate optimisation/scheduling on sculptured surface machining: A comprehensive review, applications and future directions. International Journal of Advanced Manufacturing Technology 55, 1037–1067. doi:10.1007/s00170-010-3131-3.

[9] Mauthner, G., Ehrendorfer, M., Trautner, T., Ramsauer, C., Plakhotnik, D., Bleicher, F., 2021. Method for data-driven nc-code optimization based on dexel material removal simulation and tool holder vibration measurements. Procedia CIRP 104, 1131–1136. URL: https://www.sciencedirect.com/science/article/pii/S221282712101088X, doi:https://doi.org/10.1016/j.procir.2021.11.190. 54th CIRP CMS 2021 - Towards Digitalized Manufacturing 4.0.

[10] Möhring, H.C., Nguyen, Q.P., Kuhlmann, A., Lerez, C., Nguyen, L.T., Misch, S., 2016. Intelligent tools for predictive process control. Procedia CIRP 57, 539–544.

[11] Plakhotnik, D., Berglind, L., Stautner, M., Euhus, D., Ozturk, E., Fuertjes, T., Murtezaoglu, Y., 2019. Visualization of Simulated and Measured Process Data: A Digital Twin Approach to Improve Machine Tools Lifecycle. pp. 225–233. doi:10.1007/978-3-030-02203-7_14.

[12] ProMicron GmbH, 2021. Cutting force measurement - measure forces directly at the tool. Website. https://www.pro-micron.de/spike/?lang=en (last downloaded 2021-12-03).

[13] Ramsauer, C., Bleicher, F., 2021. New method for determining single cutting edge breakage of a multi-tooth milling tool based on acceleration measurements by an instrumented tool holder. Journal of Machine Engineering 21, 67–77.

[14] Ridwan, F., Xu, X., 2013. Advanced cnc system with in-process feed-rate optimisation. Robotics and Computer-Integrated Manufacturing 29, 12–20. URL: https://www.sciencedirect.com/science/article/pii/S0736584512000543, doi:https://doi.org/10.1016/j.rcim.2012.04.008. extended Papers Selected from FAIM 2011.

[15] Ridwan, F., Xu, X., Ho, F., 2012. Adaptive execution of an nc program with feed rate optimization. International Journal of Advanced Manufacturing Technology 63, 1117–1130. doi:10.1007/s00170-012-3959-9.

[16] Schörghofer, P., Pauker, F., Leder, N., Mangler, J., Ramsauer, C., Bleicher, F., 2019. Using sensory tool holder data for optimizing production processes. Journal of Machine Engineering 19, 44–56. doi:10.5604/01.3001.0013.4079.

[17] Siemens Global, 2021. Adaptive control monitoring — production and process optimization in cnc manufacturing — siemens global. Website. https://new.siemens.com/global/en/products/automation/systems/cnc-sinumerik/digitalization/manufacturing/adaptive-control-and-monitoring.html (last downloaded 2021-12-03).

[18] Suprock, C., Fussell, B., Hassan, R., Jerard, R., 2008. A low cost wireless tool tip vibration sensor for milling. doi:10.1115/MSEC_ICMP2008-72492.

[19] Surmann, T., Enk, D., 2007. Simulation of milling tool vibration trajectories along changing engagement conditions. International Journal of Machine Tools Manufacture - INT J MACH TOOL MANUF 47, 1442–1448. doi:10.1016/j.ijmachtools.2006.09.030.

[20] Third Wave Systems, 2021. Toolpath level analysis and optimization. Website. https://thirdwavesys.com/machining-modeling/productionmodule/ (last downloaded 2021-12-04).

[21] Vitr, M., 2012. CAM-NC-Kopplung für einen durchgängigen, bidirektionalen Informationsfluss zwischen Planung und Fertigung. Ph.D. thesis. RWTH Aachen University.

[22] Zhu, L., Liu, C., 2020. Recent progress of chatter prediction, detection and suppression in milling. Mechanical Systems and Signal Processing 143, 106840. URL: https://www.sciencedirect.com/science/article/pii/S0888327020302260, doi:https://doi.org/10.1016/j.ymssp.2020.106840.

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