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adaptive control,
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USING SENSORY TOOL HOLDER DATA FOR OPTIMIZING PRODUCTION PROCESSES

Today's highly automated manufacturing specifies the service time of a tool in a way that the tooling costs are balanced against the potential costs of a tool failure. However, the potential cost induced by a tool malfunctioning are rather high. Therefore, the current state-of-the art tackles this issue by replacing the tools prematurely at fixed intervals. To tap into the potential of under-utilized tool runtime this work purposes the use of sensory-tool holders and an interfering feedback loop to the machine tool control system. Besides its real-time closed loop control, to avoid tool failure, it also provides data in the context of (a) the work order, (b) the produced part, (c) the NC-block and command line, on (d) specific machines. Based on this data an ex-post analysis to optimize tool-life and productivity scenarios becomes possible, e.g. custom NC-programs for certain work-orders, configurations and machines. Furthermore, downstreamed work steps can be changed e.g. only to measure produced workpieces if abnormal vibrations are reported by in-process-monitoring.

1. INTRODUCTION

Manufacturing companies aim to produce components at minimum costs resulting in exactly the specified quality, which necessitates stable process conditions to result in high yields. A correct combination of tool, material with an appropriate cutting strategy, the right machine tool and a suitable clamping situation are generally considered as the basic requirements.

However, in order to fulfill the needs of the market by providing a high level productivity, producing under very stable conditions at any time is inherently conflicting. Doing so, would require sublime planning, specialized fixtures and dedicated tooling for every single step, being very much at odds with general-purpose-machines and versatility trends induced by small batches. Different approaches are used to tackle unstable processes. As published in [1] two scenarios for the reduction of chatter from a process and a structural

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perspective are presented. Whilst the structural perspective considers additional damping systems and adjustments on the construction of the machine tool itself, the process perspective deals with offline and online adaptions, e.g. the adaption of the spindle speed. For the online adaption of process parameters in order to avoid chatter, the process has to be monitored. Modern machine tools use several sensor systems. Hence, the measurement of spindle- and axis drive – power can be used to gather process information, too. In rough machining these signals even enable the detection of tool failures. When it comes to finishing processes with smaller tool engagement at the workpiece, the detection of instabilities becomes more and more of importance.

This work is largely based on the experiments by the Institute for Production Engineering and Laser Technology (IFT) of the TU Wien together with the MyTool IT GmbH and Schunk GmbH & Co. KG to develop a process control and monitoring system that uses a sensory tool holder (STH) to detect and analyze vibrations in machining operations. The parameters feed and spindle speed are adapted in case of unstable machining conditions in order to avoid tool breakage or chatter marks and, thus, insufficient quality of the work piece finish surface. However, besides in-process adaption, the overarching goal is to increase the productivity of the manufacturing system. To harness the full potential of the data from the sensory tool holder, the signals are provided to a more abstract data processing platform. The factors leading to the demand for such a platform are (i) a lack of production context on the sensory level, (ii) the need for collecting and connecting data from different sources (e.g. the machine tool and connected systems), (iii) steep storage requirements for historic data, and (vi) missing computational power for any of these operations.

Typical use-cases which can be done by such a platform are to determine control parameters for similar manufacturing processes, to provide them to users of the sensory tool holder and finally the adaption of cutting parameters in the NC-programs based on historical data. Therefore, an orchestration platform called centurio.work [2] was developed fulfilling the requirements mentioned above.

This paper is structured in six chapters. In Chapter 2 an overview about the state of the art regarding process monitoring and in-process control is given. Furthermore, the sensory tool holder solution and the approach for data collection in production is discussed. Chapter 3 presents the difference in signal analysis for measurements in a rotational system like the sensory tool holder as a basis for tool life prediction. In Chapter 4, the communication structure of the closed feedback loop and interfaces to the machine control system to interfere in case of instabilities like chipping on cutting edges is described. Chapter 5 shows, how centurio.work is used as a platform for data collection and depicts how process suggestions based on date analytics can be derived. A conclusion is given in Chapter 6.

2. STATE OF THE ART

2.1. PROCESS MONITORING AND IN-PROCESS ADAPTION

An overview about products and academic papers regarding different approaches for process monitoring is presented in [3]. Hereby, the approach of in-process parameter adaption can be recognized in "Machining Navi" from company Okuma. Oscillations are measured with sensors in the spindle or microphones and the spindle speed is automatically adapted in order to reach stable zones [4]. Furthermore, the Manufacturing Automation Laboratories Inc. offers the solution "ChatterPro" using microphones to detect instabilities and applies new set points for spindle speed in case of chatter [5]. It is important to note, that process responses are observed through a permanently varying channel. For example, the natural frequencies of the machine structure shift from resilience measurements on stationary machines with an open force flow compared to the machining process, in which the force flow is closed [1]. For a constant frequency response from the excitation to the measuring point, the distance between the cutting zone and the sensor must be constant. The smaller this spatial distance, the higher the potential resolution at which process induced effects can be observed. That makes an integration of sensors close to the cutting zone and thus in the tool holder desirable. Moreover, an integration of sensors in the tool holder does not need any modification of the machine tool in vicinity of the cutting zone, which is an advantage compared to microphone systems.

The company promicron follows this approach with their "spike in spindle" and "spike mobile" products. The system spike mobile uses force sensors to measure the bending moments and force quantities in the tool holder [6]. However, the tool holder presented in this paper measures acceleration, which enables to detect chatter vibrations in higher frequency ranges compared most commercially available counterparts.

2.2. SENSORY TOOL HOLDER

The utilized tool holder uses acceleration sensors to measure tool vibrations. Aside its natural vicinity to the cutting zone, its second main advantage is the consistent distance between sensor and cutting zone, compared to stationary sensors. Fig. 1 shows a sensory hydraulic chuck tool holder equipped with single-axis acceleration measurement technology. The functional model presented in [3] confirmed the proof of concept for a real time closed loop in-process control based on acceleration signals.

Fig. 1. Sensory tool holder

In order to move from a functional model towards an industrial application, the wireless data transmission was changed from an analog system to a digital wireless transmission standard.

Aside from a more stable transmission regarding signal interferences, the main advantage of a digital transmission is the opportunity to add two-way communication and thus more functionality to the system. This helps to achieve the ability to transmit many logical signals via one single connection. Besides obvious expansions like multi-axis acceleration sensors or a mix of different sensor types, it is possible to store and serve tool related information like number of cutting edges, tool geometries/tool presetting date or runtime statistics.

2.3. DATA COLLECTION

Data collection is nothing new in the manufacturing application, its an integral domain of the production management and planning. The gathered data were used for different production optimization issues like the reduction of waste by improved in-process quality insurance or the determination of the overall equipment efficiency (OEE). Due to new technologies and initiatives summarized as the Industrial Internet of Things (IIoT) or Industry 4.0 lead to new opportunities. This is based on cheaper and smaller sensors, easy to integrate computers, e.g. raspberry Pi, and increased computing power.

For many big-data applications involving the high-performance storage and analysis of log-data, Elasticsearch [7] in conjunction with the Kibana [8] analysis platform were established as the de-facto standard. An alternative solution to Kibana is Grafana [9], which concentrates on the graphical aspect of analysis, but stores the data in more traditional databases or time-series databases, respectively. For storing time-series data Time Series Database (TSDB) is an established solution. One of the most widely used system is influxDB [10]. The reasons for using TSDBs are the high performance in data writing and queries, the scalability, the data compression and the improved usability for simple analytics.

In the manufacturing branch, one of the most known platforms for storing data is Siemens Mindsphere [11]. Mindsphere offers several connectors to machines, PLCs and other hardware equipment. These connectors can run on edge hardware called MindConnect and allow a secure transport of the information to the Mindsphere cloud platform. The platform represents an open system approach, which enables developers to realize their own applications connecting machines, automated units for workpiece manipulation and controls.

An alternative to Mindsphere with very similar aims and architecture can be seen in the PREDIX platform by GE [12]. The above mentioned platforms come along with some drawbacks and hindrances in implementation due to the fact that they are not decisively designed to cover actual problems of discrete manufacturing processes. They are much more focusing on tracking/modelling the dependencies between data pools. This leads to a potential discrepancy between what happens, and what is perceived to happen especially in a highly dynamic production environment with ever changing products and involved machines.

3. SIGNAL ANALYSIS

The difference between a stationary sensor and a rotating sensor fixed to the tools coordinate system is relevant for the understanding of the signal processing. In order to illustrate, a model of a flexible grinding tool can be used to describe a tool with no distinct cutting edges. Hence, during the grinding process a statically applied sensor measures a nearly constant force signal resulting in the forces at the point of contact while grinding, the torque at the frame of the tool holder or the force needed to clamp the workpiece.

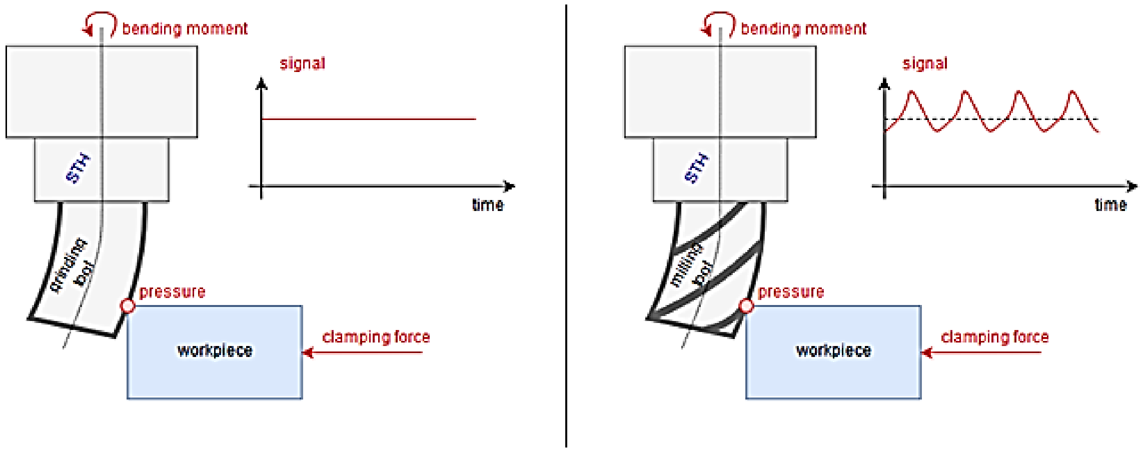

Fig. 2. Vibration generation

By replacing the grinding tool by an endmill, the previously constant signal now varies and shows a time dependency induced by the individual cutting edges, which occurs with tooth passing frequency. Each cutting edge causes the same generic vibration. When the signal of a stationary applied acceleration sensor is compared to the signal of the sensory tool holder, the signals show significant differences. Using the rotating sensor, the acceleration caused by the cutting edges is detected differently due to the current orientation of the acceleration-sensor relative to the work. Using a stationary sensor, which is fixed in the machine coordinate system, each cutting edge is registered as identical transient.

During one rotation of the spindle, the sensors sensitive axis forms a vector product with the present excitation. A constant signal in the stationary system appears as sine-function in the rotary system as illustrated in Fig. 3. Equivalently, transients induced by distinct cutting edges affects the resulting measuring signal, depending on the orientation relative to their position and the sensor's sensitive axis. This effect can be described as a nonlinear modulation of a signal. As a result, the output caused by an ideal milling tool with four cutting edges depicts Fig. 3, right. The generation of the STH-signal can be simulated by using the equation (1) [13, 14].

$$sig_{\mathrm{rot}(t)} = \vec{e}_{\varphi(\mathrm{t})} \cdot \overrightarrow{sig}_{\mathrm{inert}(t)} \tag{1}$$

with: $sig_{\mathrm{rot}(t)}$ – signal of the rotating sensor, $\overrightarrow{sig}_{\mathrm{inert}(t)}$ – vector-valued signal of the statically applied sensor, $\vec{e}_{\varphi(\mathrm{t})}$ – current vector-orientation of the rotating sensor.

Furthermore, the orientation of the sensor implementation on the tool holder body comes along with the effect, that a sensor in the STH cannot detect the vibrations caused by all of the cutting edges. Choosing an application with a perpendicular orientation of a cutting insert relatively to the sensitive axis of the sensor, vibrations cannot be determined. On the contrary, machine vibration and chattering effects are, in general, multiaxial movements, so that the STH is able to detect parts of those movements anyway. However, these effects cause the necessity to treat signals out of the STH differently compared to measurement values gained from stationary sensors. Based on signals modeled from a perfect milling process, instabilities and process abnormalities can be detected by evaluating the STH's signal.

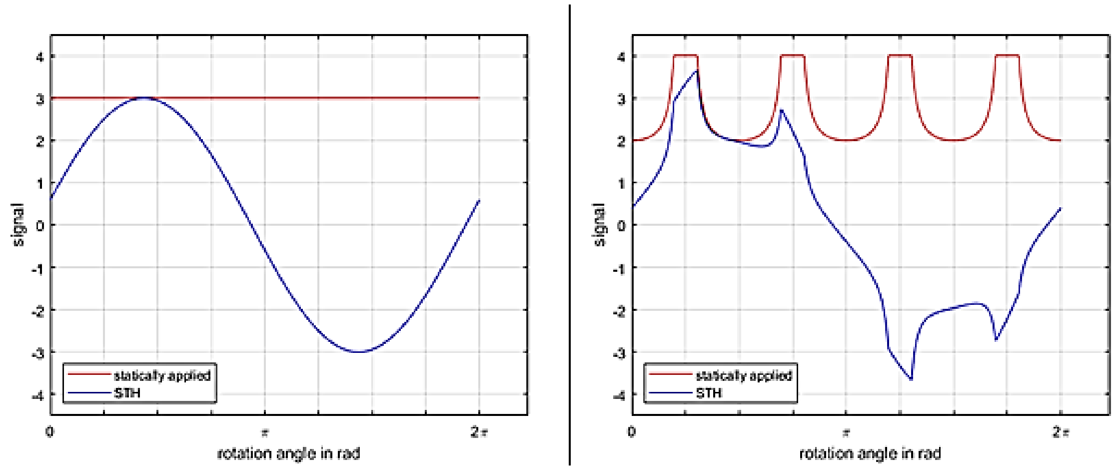

Fig. 3. Difference in measuring signals due to sensor application – left: flexible grinding tool, right: endmill

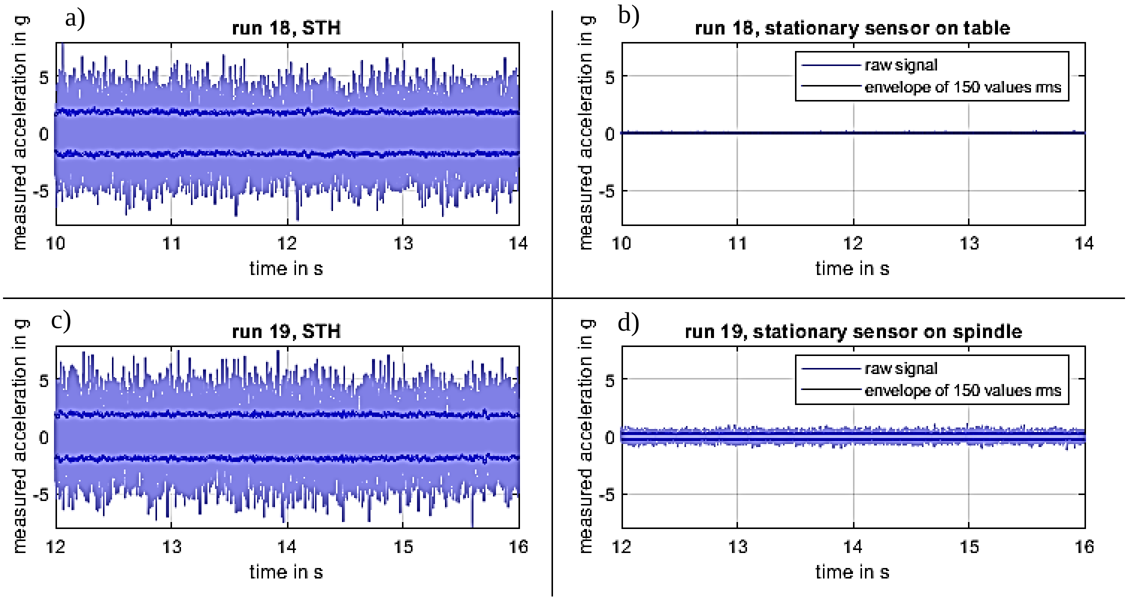

Fig. 4. a): Vibration of run 18 was measured at the STH and stationary at the table, (b), c): vibration of run 19 was measured at the STH and stationary at the spindle (d)

Tool: D25 mm-insert milling cutter, Material: EN AW-5083 (AlMg4,5Mn), Machine: DMG Mori DMU 75 monoblock, Spindle speed: 3,000 rpm (run 18) / 3,600 rpm (run 19), Feed rate of 500 mm/min, Cutting width 20 mm, Cutting depth 2 mm

Especially tool breakage, chipping of a single cutting edge and chattering generate particular artefacts in time domain as well as in the frequency spectrum of the vibration signal. As shown in [3], tool fracture and instabilities can be detected in drilling processes with small tool diameters, e.g. 3 mm using a sensory tool holder with acceleration measurement. However, if this concept should be expanded for in-process tool condition monitoring regarding tool wear, the thermal influence plays an essential role. This would require temperature measurement close to the cutting edges. A real time temperature measurement with embedded thin-film thermocouples in milling is presented in [15]. In this work, a slip ring is used to proceed the signals from the rotating tool to the "Signal Processor". Therefore, it would be desirable to combine this development with the presented sensory tool holder system.

Fig. 4 shows the time domain of acceleration signals measured in a cutting experiment with the sensory tool holder and stationary applied sensors. It illustrates that the acceleration values differ depending on the position chosen to measure it. This results show that no useful measurement values for the assessment of process condition results by a stationary applied sensors. A slight difference between n = 3,000 rpm and 3,600 rpm can be determined. Besides the constant distance between the point of measurement in the tool holder and the cutting edges, the relative stiffness is a crucial issue for signal detection in the holder. Due to the construction of serial kinematics in modern machines, tooltip and holder are among the weakest points. Thus, cutting forces cause high amplitudes of motion in these parts. Vibration should be measured at the positions where motion and thus acceleration values occur with greater magnitudes. The previously discussed effect of rotation is only visible if a small time period of signals is inspected in detail.

4. IN-PROCESS CONTROL LOOP

As already mentioned, a closed loop control of acceleration signals is realized to establish an in-process adaption of feed and cutting speed. The signal acquisition is realized by a sensory tool holder featuring an acceleration sensor and bi-directional wireless data transmission. Fig. 5 illustrates the communication structure of the presented real time control system. Via a stationary transceiver unit, the signal from the sensory tool holder is forwarded to a "Signal Processing Unit" (SPU, cf. [3]). The SPU processes and determines the process stability or chattering as well as tool condition based on the presented signal analysis approach. Coupling the SPU with the NC-control system of the machine tool enables to apply in-process parameter adaption. Hereby, the SPU analyzes the signal from the STH and provides an estimate for the current state of the cutting process. A rule engine in the SPU decides if counter measures are necessary and, if so, proceeds new set points for feed rate and rotational speed depending on defined optimization strategies. The latter are set up on constraints derived from process and machine physics as well as the material behavior and include the worker´s experience.

The SPU fulfills two operational functions; on the one hand side the real time closed loop control capabilities of the process stability and on the other hand side supplying data to the machine tool operator or providing feedback information to the manufacturing execution level. An efficient in-process control needs to keep the time from detecting instabilities to a reaction of the machine tool drives as short as possible. Fig. 6 shows different options to apply new set points for feed rate and spindle speed on the basis of a Siemens 840 CNC control system.

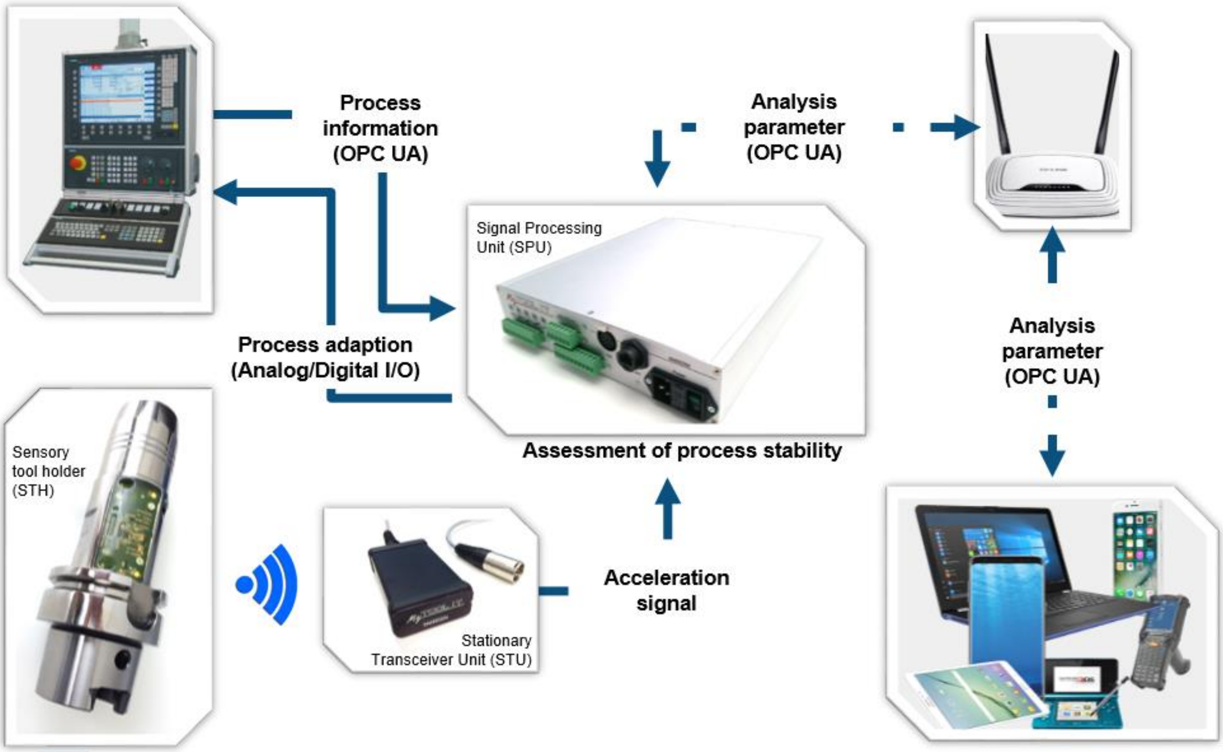

Fig. 5. Communication structure of the in-process control system

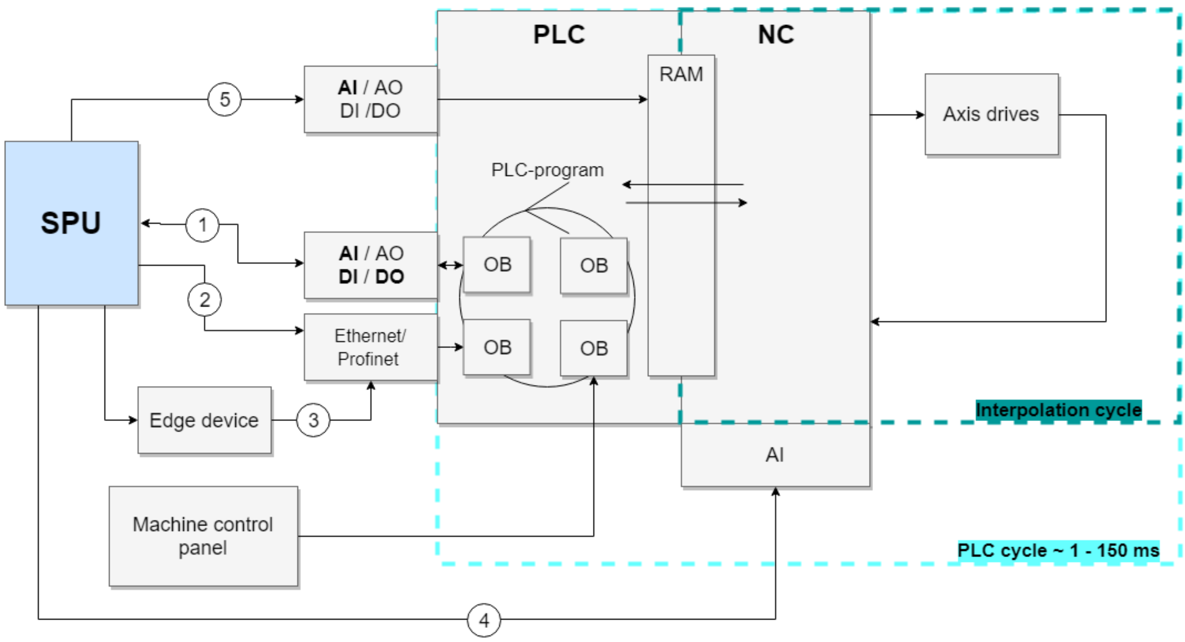

Fig. 6. Interfaces for the SPU to Siemens control system

The programmable logic controller (PLC) with its input/output (I/O) modules exchanges data with the numerical control (NC) via the random-access memory (RAM). The PLC program, which consists of a sequence of organization blocks (OB), operates cyclically. Data blocks (DB) are used as non-persistent storage of data and can be written by PLC-program itself or externally. Values can be provided in a DB which then can be further proceeded in the machine. E.g. the machine control panel is connected to the PLC and also provides its values in a DB. The NC controls the drive axes and reads their current values [16]. The signal processing unit (SPU) communicates with the control system via the I/O modules and the programming interface (Ethernet/Profinet) of the PLC. As a further option illustrated in Fig. 6, an edge device is a separate computing entity, which interfaces with the PLC. In this setup, the SPU can be seen as part or example of an edge device. Those devices gain their name from being close to the data source or "edge of the machine" while serving functionality usually attributed to centralized systems. Regarded from the networks perspective, edge computing in general depicts the shift of the data storage, computer performance and software to the point where it is needed in the computer network, offering unparalleled low latency at network loads, when compared to a centralized design [17]. Therefore, setups like these are a prime example where choosing a suitable, more modern, system topology is an enabling factor for this technology setup. If a setpoint of the SPU is proceeded via the PLC, the feedback loop operates within the PLC cycle time, which is about 10–30 ms, depending on the implementation of the PLC-program. If the setpoint is called directly in the NC, the feedback loop can operate within the interpolation cycle time, which is one magnitude smaller than the PLC cycle time [16]. Therefore, in order to improve the control of the machining process by reducing the cycle time of the feedback loop, it is desirable to proceed the setpoints directly via the NC. Subsequently, there are five different feasible ways how input data from the SPU can be proceeded to the axis drives. The first option uses an analog signal; the SPU generates this analog signal which is applied to the analogue input (AI) of the PLC. The corresponding value is then stored in a specifically implemented DB and mapped on an overwrite (OVR) variable, which is used by the NC and controls the drive axis. The implementation of the DB also has to deal with the other options of configuring an override (e.g. control panel). In this case it was chosen to multiply all different override sources to gain the final value. As a second option, the SPU is attached to the PLC via a network interface. It allows to set a value in a DB very similar to option 1 just without the analog input module. In option 3, the SPU implements or interacts with an edge device. The edge device uses a real-time capable network protocol like industrial ethernet to interact with the PLC. The fourth option uses the system variable $A_INA[n], which offers to access the value of the analog NCK-Input [n] directly in the part program or via synchronous actions. Furthermore, this analogue input value can be adapted by the PLC program [16], which means, the machine operator keeps the upper hand to change the process parameters via the potentiometer on the control panel. The final option 5 shows a PLC periphery, which is directly addressable from the NC. The input value from the AI is proceeded via a fast data channel and uses the system variable $A_PBx_IN. An update rate reading this variable is definable e.g. every third interpolation cycle [16]. To sum up, options 4 and 5 represent the fastest access for external in-process control. However, each option necessitates the machine tool producer to implement the interface. Options 4 and 5 are usually more time- and cost- consuming compared to the options 1 to 3, which are, by far, much simpler to implement. Option 3 can be regarded as state of the art and is in tune with ongoing trends. It provides high flexibility and still maintaining encapsulation of the NC-subsystem.

5. EXPERIMENTAL SETUP OF CENTURIO.WORK

Centurio.work is a modular secure platform based on processes [2]. Its intent is to simplify the integration of heterogeneous systems throughout the whole automation pyramid, by utilizing a true service-oriented approach and advances like the BPMN [18] modelling language, and flexible execution [19, 20].

Its flexible architecture, as depicted in Fig. 7 CARCH above, allows integrating and orchestrating different industrial software, hardware e.g machines and robots and employees. For connecting different entities a module called data provisioner (DP) is used. The data sources are connected through custom adaptors, that are implemented for different protocols like OPC UA, S7 or even custom low-level socket based protocols. The DP determines at runtime which adapter is used. The communication between the data provisioner and other modules in the orchestration container is realized with HTTPS.

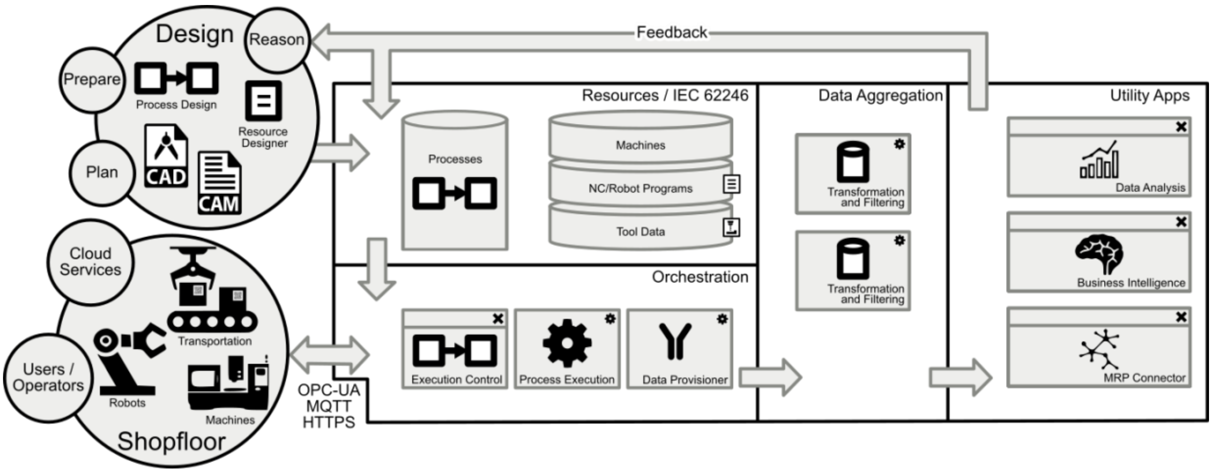

Fig. 7. CARCH: centurio.work architecture [2]

The centurio.work platform is currently evaluated in conjunction with the sensory tool holder for producing a complex part for an industry partner. The communication between the SPU and centurio.work is realized with the OPC UA interface. Each data collection has the following properties:

- A first level process – spawn the production of individual parts based on orders from an ERP. Furthermore, assign and print QR codes for each part to identity the part throughout the production.
- Second level processes for each part – the recipe how to produce the part. May contain multiple machining and quality control steps (either manual or by measuring machines).

- Third level process for each resource – the interaction with individual machines. For example for each turning and milling step from level 2 there are recipes for different machines how to set NC-programs, parameters and start production. This level also is intended to contain instructions and user interfaces targeting machine operators in order to perform a setup.
- Fourth level process for each resource – spawned for individual machining (i.e. spawned from the third level for milling/turning tasks). This level contains the logic to control the sensory tool holder, including user interfaces for changing the properties of the tool holder.

The BPMN processes described above are depicted in Fig. 8.

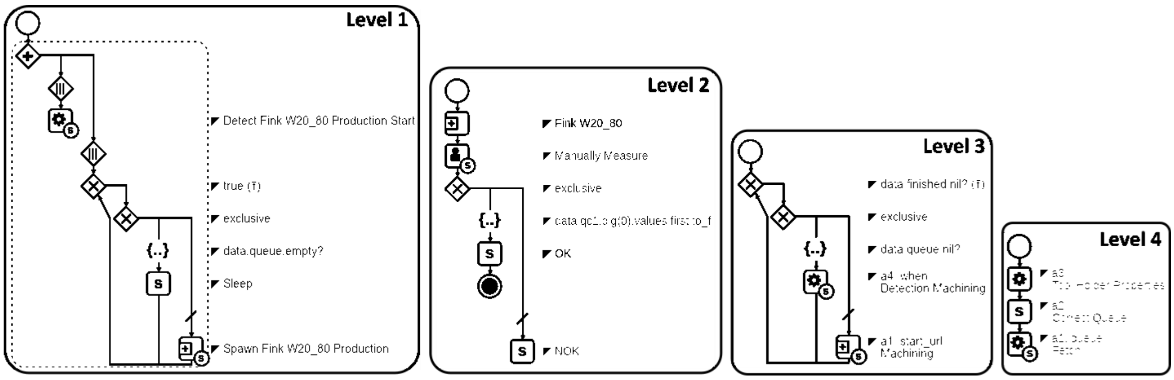

Fig. 8. BPMN Data collection processes

The example data package provided by this paper has the following content:

- /processes/: The processes in BPMN tree based XML format and as PNG image,
- /logs/: IEEE 1849-2016 XES standard based log files, tuned for high-performance data collection,
- /logs/4d96d60b-1ea6-4cc0-a454-391be8d86c67.xes.yaml: log for first level process,
- /logs/parts/*: log files corresponding to each each part and level (2, 3, 4).

The centurio.work data collection mechanism has been evaluated in [21]. Over 50 GiB of data for five products from industry application have been collected. The data analysis focuses not purely on individual machining tasks, but on the compound data set that spawns the multiple production sets, tool information and automatic measurement steps. Thus, data from the sensory tool holder offers the potential to contribute to the higher level process improvements such as skipping measuring steps in certain situations. The performance of the data collection mechanism was sufficient for data packages of up to 200 KiB at a frequency of 50 Hz (throughput of 10 MiB/s).

6. CONCLUSION / SUMMARY

As the theoretical background in Chapter 2 shows, at least biaxial tool holder measurements are needed to match up the stationary sensors to sensory tool holder based measurements. However, the results indicate that sensory tool holders allow more robust vibration analysis due to their constant distance to the cutting zone. However, there are many practical limitations to this approach since the space and energy constraints in this application are stringent. The presented technical advancements in being able to outfit a sensory tool holder with many and different kinds of sensors is an important step. Especially, for in-process tool condition monitoring regarding tool wear, the thermal influence plays an essential role and need specific consideration. Therefore, it would be desirable to combine ongoing research work in the field of embedded thin-film thermocouples on milling tools for temperature measurement close to the cutting edge, as mentioned in Chapter 3, with the presented sensory tool holder system. However, data analysis needs to be expanded in order to make use of this option. Digital communication in the field of machine tools offers many options, but also asks for many compromises when dealing with a multitude of sensors. Ongoing research is targeted towards measuring a different process parameters, from the tool holder, the machine and the final workpiece, in order to identify the most significant dependencies. The centurio.work framework and its ex-post analysis capabilities can fulfill these requirements. Only if those dependencies are understood, fast and efficient real-time analysis routines can be implemented to control the manufacturing process. This work shows that chatter in face milling is already maturing in this respect – as only one of many applications. Applying the approach of a tool life time prediction using a sensory tool holder and a closed feedback loop the residual tool life time can be estimated and catastrophic tool failures can be avoided. As a result, the tools can be utilized to their full potential while not giving up on the low failure rate.

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