Advanced Milling Simulation and Information Management

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ABSTRACT

This paper presents results of coupling actual milling processes from the aircraft industry to a related simulation by collecting process data. This allows both, an immediate real time process monitoring on the one hand and a long-term evaluation of the process reliability on the other hand. The immediate process monitoring compares the time series of the spindle torque with the precomputed simulation results and stops the milling process when there is a significant deviation between both. The long-term evaluation of the spindle torque is used to find anomalies in the milling processes like a drift of cutting forces, frequent tool breakage in the same NC-program over a lot of workpieces, or to analyse the tool wear behaviour.
To build up such a system the data flow between the NC-programming, the machines, and the simulation system had to be analysed to build an information model. This has been necessary for an optimal development of the communication channels between all subsystems (CAM-system, milling machine, process monitoring system, and simulation) which were originally not meant to work together. Therefore, a big challenge has been to transform a theoretical information model into a running short- and long-term process monitoring system that not only works in a university environment but in the actual aircraft industry as well.

INTRODUCTION

Milling

Milling is a machining process that uses a milling cutter to remove material from a workpiece. The milling cutter is a rotary cutting tool with multiple cutting edges. The cutting edges come into contact with the workpiece, cutting away material in small chips. The cutter is typically mounted on a spindle, which rotates at high speeds, and the workpiece is held in a fixture or clamp to keep it steady (Fig. 1). The cutting edges are designed to be geometrically well defined and sharp to provide a cutting action that is as efficient as possible.
In the aircraft industry milling is commonly used to produce complex structural integral parts of sizes ranging from 100 mm up to 10 m. Particularly the large parts require safe machining processes of high reliability. A tool breakage may lead to scrap and to costs of some 10000 €. Also, the quality of the surface finish and dimensional accuracy of the workpiece is of high importance and depends on various factors such as:

- The type of milling cutter being used
- The dynamic vibration behaviour
- The spindle speed and feed rate of the cutter
- The material properties of the workpiece
- The rigidity of the machine and fixture

Since milling of geometrically complex parts is a very sophisticated process it is necessary to monitor as many process parameters as possible to assure the needed high quality and efficiency. In addition to that, any additional information about process parameters helps to investigate the reason for occurring problems. The following parameters are of high interest when analysing milling processes:

- Actual tool diameter. To reuse tools, they are reground after their lifetime. This lowers the diameter which is automatically compensated by the milling machine. Anyway, reground tools behave slightly different than new tools.
- Wear state. Worn tools produce higher forces and therefore higher surface error.
- Spindle torque. From the measured spindle torque one can analyse if the process ran like intended. This can be done by comparison between measured and

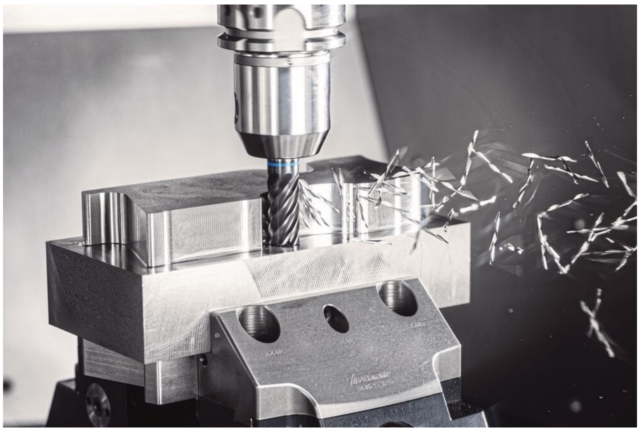

Fig. 1. In milling a moving and rotating tool with cutting edges removes chips from the stock and therefore forms the final shape of a work piece. [Image: Hoffmann GmbH Qualitätswerkzeuge]

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simulated torque progressions (Fig. 6).

- Actual tool identity number and position in the NC-program to relate reality to simulation.
- Timestamp and job number in order to relate measurements to the specific part.

The acquisition and analysis of some of the above-mentioned data is subject to this paper.

Research Objectives

The goal of the research project "AUTODAT - AUTOmated, holistic use of manufacturing DATa" is to increase the utilization of cutting machines while at the same time making better use of tool resources and ensuring a consistently high level of quality. To achieve this, the data that is already collected in parts in production today must be made usable, evaluated holistically and automatically, and correlated to one another and to quality data as well. In addition, further high frequent measurement data must be collected and evaluated in relation to the condition and reliability of the process, tool and workpiece. The Jade University for Applied Sciences supports the project partner Premium AEROTEC GmbH (PAG) in the AUTODAT project with expertise in the areas of information modelling, condition monitoring and user experience design in order to optimize the process chain and the flow of information in milling processes and to achieve economic advantages for the project partner.

One main objective of the research work is to close the information gap between the machine operators and the NC-programmers. The operators currently report problems such as tool breakage or bad processes by filling out a paper report with a low level of details of what might have happened and at which position in the NC-program. This report together with the related machined part is then sent to the quality inspection. It often takes some days time until all the information reaches the NC-programmer who has to investigate the reason of the problem. With the acquisition of high frequent process data such as spindle torque together with some meta data about time and date, the milling tool, and the related part the NC-programmer can use the milling simulation in order to find the problematic position in the NC-program and compare the measured data to the simulated ideal one. This strongly helps to investigate the reasons for bad processes or low quality of the part.

Recent achievements are:

- Tool wear model [18] made possible by the measurement of the influence of tool wear on the spindle torque and therefore on the cutting force.
- Process Condition Monitoring information from sensors mounted on the workpiece.
- A Dashboard for the visualization of the derived information

Structure

After this introduction, the unique simulation capabilities at PAG are presented in the following section, along with examples for the recent results. The integration of additional information from process monitoring, tool information and quality assurance into the existing information flow is followed by two implementation variants on different technical readiness levels.

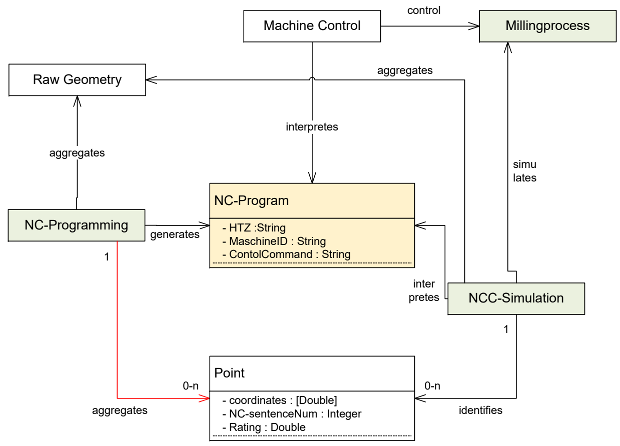

Fig. 2. Excerpt of the UML diagram as a result of the object-oriented analysis

EXTENDED SIMULATION CONCEPT

The implemented simulation environment at Premium AEROTEC and the AUTODAT project developments show unique specialties in the CAD/CAM and simulation toolchain and methods, which are described in the following section.

Information model

This information model is the basis for analysis and visualizations. Furthermore, a model should support the documentation of the system and the reusability of parts. The model also serves as a means of communication for interdisciplinary cooperation and makes it possible to identify and map potential that has not been noticed until then.

Fig. 2 shows a fraction of the simplified information model, which focuses on central classes in the context of this paper for communication purposes. The model has been developed as a UML2 class diagram, see UML Infrastructure definition [12]. It is a result of an object-oriented analysis [1], [7], [13]. Different instances of the model can be derived from the structure, e.g. JSON notation for machine communication or relational database models.

Fig. 2 illustrates the raw geometry of the blank, which is the relevant starting point for the programming and is aggregated by the simulation. The NC-program is interpreted by the controller of the milling machine and the *NCChip* simulation (described in more detail in the following section) likewise. The simulation identifies critical points on the surface of the tool and the workpiece and computes a maximal value for the expected torque on the tool.

Existing concepts and relations are added to the model and the model grows and becomes more detailed.

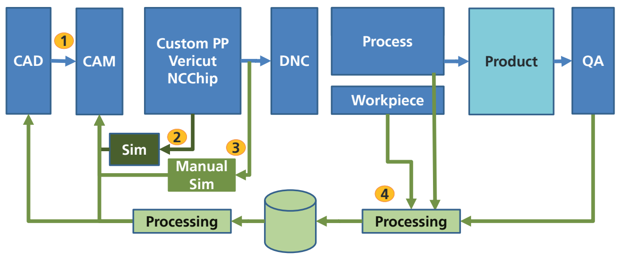

Fig. 3. Extended Simulation information flow in project AUTO-DAT
CAD/CAM: Computer Aided Design & Manufacturing
DNC: Direct Numerical Control
NCC: NC Chip as described in[15]
PP: Post processor
QA: Quality Assurance

The model has proven to facilitate a common understanding of concepts and relations in the team. In the inverse direction, the identification of new relations is a goal of the project, indicated for example between `NC-Programming` and `Point`.

Information Flow

The development of complex information systems requires a plan or, with different words, a model before the start of the development - an abstraction of reality with a focus on the essential object of observation. The aim is to avoid errors, to achieve better quality during implementation and fertilize a common understanding of the structure to the information sets. The development of an information model that meets the special requirements in aircraft construction and the current possibilities of information processing is the first step.

The extended information flow is illustrated in Fig. 3. The flow starts with the implied conventional CAD/CAM process, labelled by the round marker (1). Right after the generation of the CAM Model, derived from the CAD Model, the cutting process is verified with a two-step (inner and middle loop) approach. The inner simulation loop (2) is performed by conventional geometrical verification of the NC programs. This process is covered by commonly known CAD/CAM methods [5], [8], [10], [19] and software tools CATIA V5 (Dassault Systèmes) and VERICUT (CGTech Deutschland).

The interesting middle loop (3) is the technological simulation loop performed with the software *NCChip*, which is an individual development of the author and Premium AEROTEC GmbH. You can find details in the next section. Since this loop is independent from any information management system, possibilities and challenges arise likewise.

- The technological simulation considers tool deformation, vibration and wear to an atomic level of detail. The simulated result is often more precise than the actually milled result.
- The maturity level of the software development as managed process reaches level 2 on the CMMI maturity scale [3].
- The user group of the tool is limited to selected persons, which are trained on the job and individual experiences.
- The simulation is not integrated in the development cycle for every NC programmer. It is a manual task, which must be triggered by request and includes profile and parameter variation, tool and material definition and low-level result interpretation.
- Company critical know-how within one brain leads to a single-source of failure situation.

The outer loop (4) indicates the information flow within modern production, referring to automation pyramid (SAP, MES, etc.) [19], production information systems according to ISA-95, especially Part 2: Object Model Attributes [6], CIM related methods and tools [14], [9] and quality systems [2], [11].

The interesting middle simulation loop (3) will be described in detail in the following section to show a successful example for the aggregation of information according to the concept. The implementation of the concept leads to two different architectures with an academic and with an industrial focus.

Machining Simulation NCChip

In order to verify the geometric and technological correctness of NC-programs the technological milling simulation *NCChip* has been developed that is capable of computing cutting forces, spindle torque, tool wear, and deflections as well as vibrations of the cutting tool along arbitrary NC-programs [15], [16], [17]. The main idea of a milling simulation is the modelling of the contact situation between the cutting tool and the work piece i. e. the undeformed chip. From this undeformed chip the local cutting forces along the cutting edge can be derived and integrated along all cutting edges in order to get the overall tool load. Furthermore, the tool revolution is divided into small angular steps to

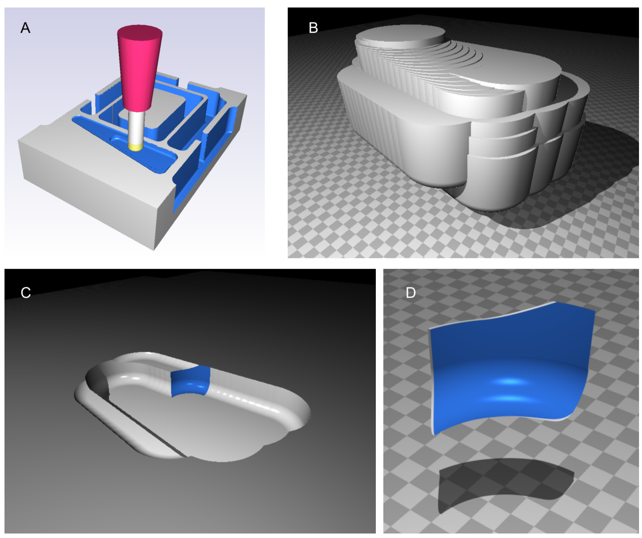

Fig. 4. The basic idea of the milling simulation is the modelling of undeformed chip forms. By a set-theoretical approach the chip D is the result of the intersection of the current tool model A with the local model of the work piece C one step before, which itself is the difference between the local sweep volume B of the earlier tools and the stock.

compute the progression of the cutting forces along the chip formation. The undeformed chip C_n at the time of the n-th chip can be modelled by a set-theoretical approach:

$$C_n = W_{n-1} \cap T_n. \tag{1}$$

Here, T_n is the model of the rotationally symmetric envelop of the milling tool tip (Fig. 4 A) at the position of the n-th chip removal and W_n is the related work piece after the n-th chip removal (Fig. 4 C):

$$W_n = W_0 \setminus \bigcup_{i=0}^{n} T_n. \tag{2}$$

The model of the union in the equation can be seen in (Fig. 4 B). The result is a high detailed geometric model of the undeformed chip (Fig. 4 D) which is the basic model for any further computation of milling forces. Please refer to [15] for detailed information.

NC-Program Verification and Optimization

After programming, the NC-code is tested by the simulation if it will exceed the technological restrictions, i. e. maximum allowed force, spindle torque or power. Additionally the milling simulation is used to optimize the feed rate in order to not waste machining time by a too low tool load. Therefore, we developed a specific optimization algorithm that optimizes the feed rate in a way that the tool gets the optimal uncut chip thickness at any position within the NC-program. Especially in the machining of titanium parts the average saving of machining time is 20% without increasing the tool wear. In the industrial environment it is not easy to ensure that simulations are always well calibrated. E. g. milling simulations need the calibration of the cutting force model which relates the uncut chip thickness to the cutting forces. This calibration must be made

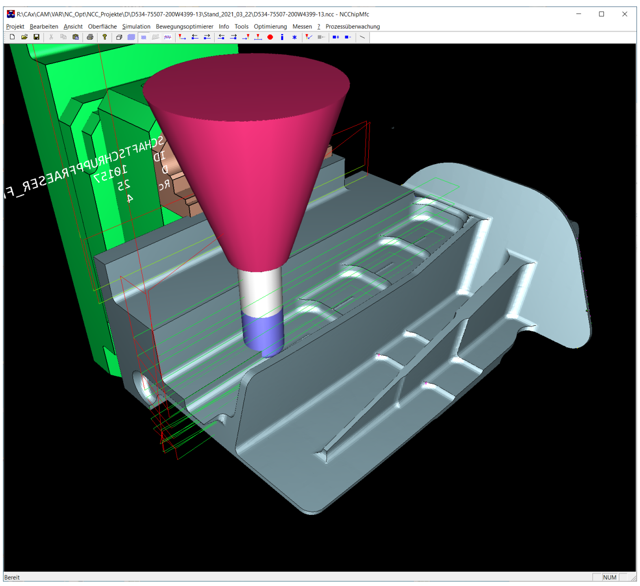

Fig. 5. Milling simulation of an aluminium latch of the cargo door of an Airbus A320. The shown tool path (green lines) of the operation relates to Fig. 7.

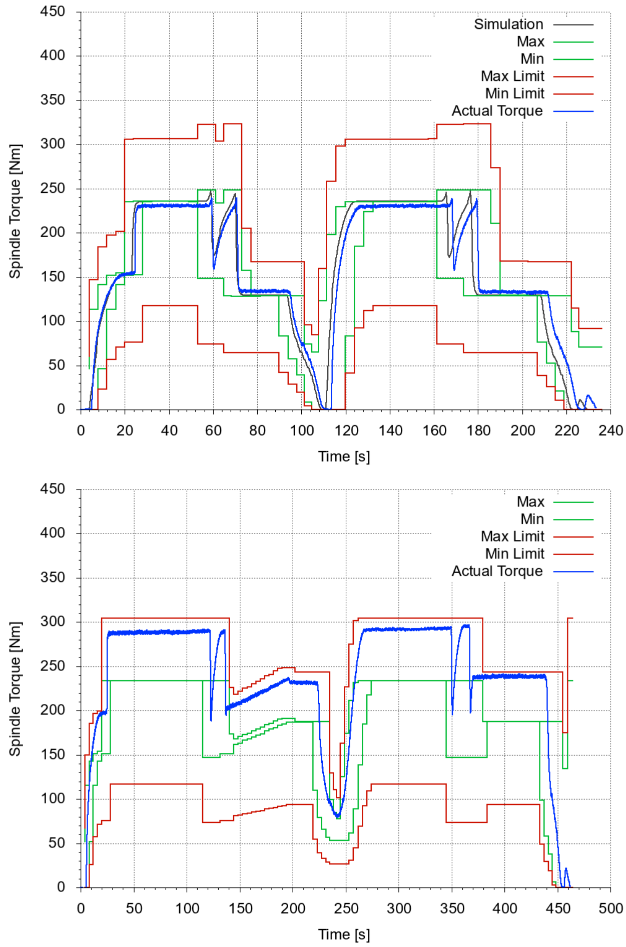

Fig. 6. Time series from two milling operations of a titanium door frame. Shown are the actual spindle torque (blue), the high resolution simulation result (black), the ideal lower resolved upper and lower limits that are given to the process monitoring system (green), and the related limits for a machine stop (red). The second image shows a similar time series but with an almost worn tool.

for each combination of work piece material and geometric form of the cutting edge of the tools. Since in aerospace industry mostly Al7075 and TiAl6V4 alloys are used and there are only a few different cutting edge geometries the calibration is not too difficult.

Anyway, in order to check both simulations against reality and vice versa, a simulation based process monitoring (PM) has been developed. Therefore, the spindle torque time series of a milling process is computed by the simulation and transferred to the milling machine together with the related NC-program. While machining the actual spindle torque is continuously measured and compared to the related simulated value (Fig. 6). In case of an obvious difference between both signals the machine stops and the machine operator may check the final reason for that.

The most interesting outcome was, that tool wear can be recognized by an increase of spindle torque. The process monitoring stops heavily worn tools before they break fatally which is a high increase in process safety. Additionally, all machining problems that cause a rise of the spindle torque e. g. breakage of a cutting insert

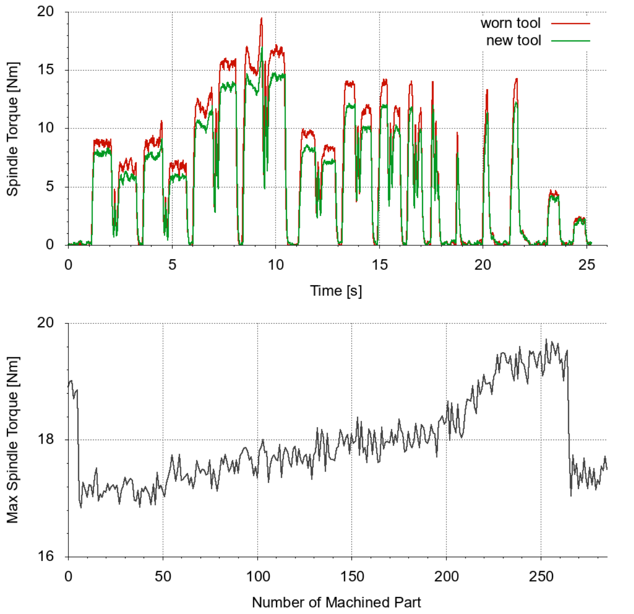

Fig. 7. Top: Two torque measurements of the same milling operation within an aluminium part. The green one refers to a new tool and the red one to a worn tool. Bottom: The time series shows the maximum torque of the above shown operation along the production of 280 parts.

can be detected. This process monitoring works immediately on the actual running milling process which can be referred as *short time process monitoring*. When storing all the process data together with the related meta data (tool ID, actual diameter, remaining lifetime, etc) and some key values (maximum, duration, etc.) from a measured torque time series a long term observation is possible.

Long-Term Process data

In the machining of titanium the tool lifetime is with 30 minutes rather short. Therefore, it is easily possible to conduct wear measurements in order to formulate an empiric wear model. In the machining of aluminium the tool life is at least 60 hours. Thus, the measurement and analysis of long term data is of high interest. Using the process monitoring system the spindle torque is measured and saved along each tool. An automatic data analysis runs each night and saves all relevant data of the torque time series (maximum torque, duration, maximum deviation between measurement and simulation, actual tool diameter, remaining lifetime, etc.) into a database. This allows to analyse e. g. the maximum torque of the same milling operation over many weeks. Fig. 7 shows the maximum torque of a roughing operation of an aluminium part over a number of 280 parts. It can be seen that the torque continuously rises due to the tool wear starting at the point where a new tool was put into the machine (shortly after the beginning of the data) until the end of the lifetime where the tool is replaced again.

Upcoming Research

With the use of long-term data it will be possible to analyse the tool wear especially for the machining of aluminium parts. Today, tools for aluminium machining are replaced after a fix time of 60 hours. In future, it will be possible to predict if a tool could be used longer. When defining a standard process for each different tool like shown in Fig. 7 from a part that is produced frequently it is possible to define a torque limit that defines the end of the lifetime. An automatic message from the analysis software to the MES-system (manufaction execution system) could invoke the replacement of the worn tool. Furthermore, the analysis software can search for anomalies in the long-term data. E. g. discontinuities in the time series mark particular events like a tool replacement (Fig. 7 after 6 parts from the beginning of the data). Other anomalies could denote tool breakages or other problems. A frequent occurrence of anomalies in the same milling operation reveals an unsafe process and a technologist can investigate and solve the problem with the help of the related high resolution torque measurements.
In addition to that, predictive maintenance of the spindle will be applied. Hereby, the idle torque will be measured at the beginning of each milling operation. A slow but continuous rise of the idle torque could show the wear of the spindle bearings. Again, a limit of the idle torque could mark the point in time where the spindle should be replaced latest in order to prevent a sudden spindle failure during a milling operation.

SYSTEM DEVELOPMENT AND IMPLEMENTATION

Implementation at Premium AEROTEC

One challenge in data acquisition is to merge data from various sources together. In the case shown here, the process monitoring systems saves the spindle torque starting from the point in time where it is turned on until it is turned off again by related commands in the NC-program. The supplier of the process monitoring hard- and software provides the possibility to relate the name of the NC-program, the number of the measurement within the current NC-program, and the timestamp to the measured data. Additional data like tool ID, tool diameter, remaining lifetime, etc. are stored in a log file by the NC-program. Using the same timestamp as in the torque measurement the data can be merged. This merging is done by a software that runs at night and fetches the torque measurements and the log files via FTP. The measurements are analysed and for each process (i.e. from each start to each end of a measurement) one data set is added to a database containing all the data from many different machines. The lower diagram in Fig.7 is the result from a database query. For the analysis of anomalies a link to the file of the measured time series of the torque signal is also stored in the data set. So it is easily possible to take a look to past processes in order to assure a high process reliability.

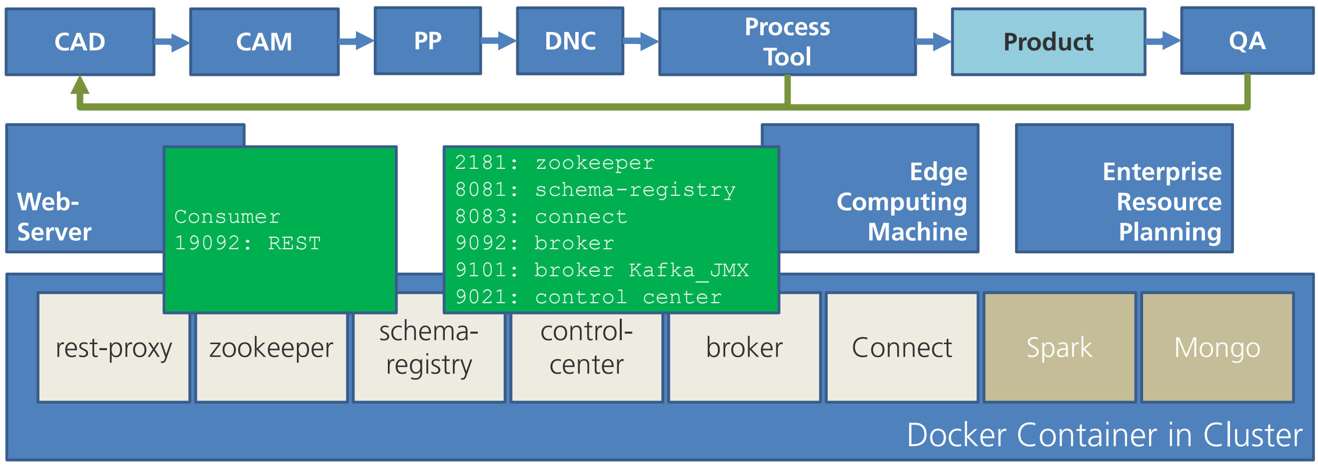

Fig. 8. Kafka Architecture for the stream processing of the milling process information

Implementation at Jade University for Applied Sciences

An extended version of the processing architecture has been developed and implemented at the Jade University for Applied Sciences and is illustrated in Fig. 8. It is based on big data approach considering scalability and near-realtime (compared to nightly fetches) processing of the information sources.

The known CAD/CAM process is illustrated on the top, while different systems, mainly in docker containers hosted in a cluster perform the following specialized functions. The explanations below follow the feedback loop from right to left. The communication is ensured via defined communication ports in green.

- The process information is gathered at the machine with a dedicated edge computing machine which is adding the tool information from the tool data management system (TDM) to the information package as well. The information from the QA is mainly stored in SAP and is aggregated from there manually.
- Different docker containers interact to transfer and process the gathered information. While `zookeeper`, `control-center` and `schema registry` are basic components for the administration of Apache Kafka, enhanced by the functionality of Confluent [4]. `Broker` handles the information queues and accepts messages from the information sources within topics.
- `Connect` connects the optional containers for persistent storage in a `MongoDB` and potential processing by Python scripts in a `Spark` container.
- The `rest-proxy` exposes the processed information via a webserver, which presents a dashboard to the interested addressee: CAD/CAM active engineers, designers and programmers.

This concept and prototypical implementation exist within a cluster at the Jade University for Applied Sciences. The obstacles for the industrial implementation are the following:

- a lack of Kafka connectors provided by the machine vendor. Since the setup is specific to the company, there is no universal product these would have to be implemented and maintained by the shopfloor IT, which all the development challenges listed earlier.
- Security regulations divide shopfloor and office network. The defined passthrough of JSON messages is not (yet) permitted.

FUTURE TOPICS & DEVELOPMENTS

The information acquisition is a crucial factor for the approaches and offers still room for improvements. The following three issues will be addressed with priority in the future. As a limitation of the approach, some error types are not identified by the setup. For example, chatter detection is not possible with the existing torque measurement, since it requires high-frequency vibration recording (1). The torque signal level during the finishing milling process is lower than the noise threshold, therefore the described approaches cannot be applied in this production phase (2). Due to the characteristic transfer behavior of the torque signal surface errors of the milled part cannot be identified in most cases (3).

In the future the integration of the academical and the industrial approaches should lead to the combination of the stated advantages and avoid existing limitations: Extended collection of raw data by aggregating further information sources (existing milling machine sensors and control information) and adding more sensors (extended condition monitoring) to the production facilities (1). Extended implementation of the information model (from the experience of the project quality information is challenging to integrate) (3). Extended analysis of the data with recent Data Mining approaches to detect anomalies in the information flow (4). Advanced professional software development (devops) to increase the maturity level of the software (5).

CONCLUSIONS

The machining simulation capabilities of Premium AEROTEC are unique in the milling industry. The presented insights as example reveal the potential of the correlation of advanced simulation information and process data. The company specific implementation of a combined CAD/CAM and simulation data management solution illustrates the opportunities and challenges. Success Factors and key lessons learned are the following:

- **Information collection** Collect as much raw but structured data as possible. The information model of this data is the key to a common understanding and information structures of e. g. databases, which emerge in the context.
- **Security concept** The early involvement of shopfloor IT is crucial to overcome information security obstacles.
- **Information competence and literacy** are a success factor, which is related to individuals. These competences are the key to out-perform the competition. Top-level management must identify, understand and keep these individuals within the company.
- The **sharing of information** is based on trust and the basis to propagate competences to upcoming generations to ensure the future success of the company.
- The **acquisition and analysis of long-term data** can reveal interesting and new process information that has been hidden so far.
- A **continuously running data recording** turns the serial production into a large laboratory that permanently produces experimental data that helps to improve both the production and the simulation.
- The **implementation of a comprehensive data acquisition** needs the tight collaboration of the technological, and IT departments of a company in order to meet all of the related restrictions and requirements.

Please contact the authors for an exchange of experiences and information.

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