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Procedia CIRP 118 (2023) 157–162

www.elsevier.com/locate/procedia

16th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '22, Italy

Industry-Oriented System Architecture for Feature-Based Data Management in CNC Machining Processes

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Abstract

Industry 4.0 promotes data-driven optimization of computerized numerical controlled (CNC) machining processes in industrial environments. In this paper, an industry-oriented data management architecture is presented, which allows automatic relation of in-process machine and sensor feedback to CAD/CAM process meta information along the product development cycle. The proposed system utilizes state-of-the-art feature-based machining technologies and open communication protocols such as OPC UA. Thereby, it ensures seamless integration into existing industrial CNC machining networks. The proposed system is demonstrated using a milling use-case with a CNC machining center and a coordinate measurement machine.

Keywords: STEP-NC; Feature-Based Machining; CAD/CAM; CNC Machining; Data Management

1. Introduction

Trends such as Industry 4.0 or Cyber-Physical-Systems have significantly increased the development and integration of sensor systems in CNC applications, as well as the produced data volumes available for analytics [1]. Concepts such as the Digital Twin build on this data by creating a virtual model as counterpart to a physical machine on the shop floor, often referred to as Machine Tool 4.0 [2]. Connecting the real machine feedback with a virtual representation provides advantages in numerous ways such as virtual machine commissioning, virtual process planning and simulation or condition monitoring to detect anomalous performance [3]. Utilizing the combination of virtual simulation capabilities and direct feedback from machines, a new generation of smart, flexible, and autonomous working machine tools is possible [4].

In order for these concepts to work, a bi-directional data interface needs to be established, enabling seamless communication between real machines, sensor technology and the virtual representation. In the context of CNC machining, several approaches for seamlessly data communication such as feature based machining or STEP-NC (ISO 14649) have been introduced in previous years, however, have not been fully adapted by manufacturing companies in day-to-day practices.

2. Related Work

2.1. Feature-based-machining for CAx environments

A fundamental concept for modern CNC machining, is the separation of part geometries and machining operations in design and manufacturing features. Features are prismatic elements such as pockets, slots or holes, created during the *Computer-Aided-Design (CAD)* and *Computer-Aided-Manufacturing (CAM)* phases of product development [5].

In the design domain, a feature is defined as a combination of geometric features, used to construct the overall shape of a component. In the manufacturing domain, it represents fixed

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10.1016/j.procir.2023.06.028

geometries, associated with process defining information such as operations, dimensions, tolerances, surface roughness or tool engagement strategies. Related techniques for automated feature recognition as well as conversion between the design and manufacturing domain, have been studied by several researchers [6].

In context of Knowledge-Based-Engineering, features provide a machining-oriented perspective on geometric elements, enabling to add a specific *Product Manufacturing Information (PMI)* such as tolerances, surface requirements or best-practice standard processes and tools [7,8]. By that, automated generation of specific process steps and toolpaths for features can be implemented in order to reduce the overall time required to create numerical control programs during the CAM product development phase [9].

Similar concepts can also be adopted for inspection tasks and coordinate measurement equipment. Recognized features in *Computer-Aided-Quality (CAQ)* software can be used for automatic generation of measuring code if the respective PMI information is associated with those features, and non-ambiguous tolerance information in line with GD&T regulations are applied [10].

2.2. Bi-directional data exchange using STEP-NC

Feature-based approaches support integrated CAD/CAM/CAQ software environments, however, are traditionally not supported by commercial CNC control systems. State-of-the-art CNC systems use the ISO 6983 "G-Code" standard, which is a low level programming language to describe machine movements in an interpretable format. The language focuses on the description of the cutter centre location with respect to the machine kinematics, eliminating higher level CAD/CAM feature information entirely [11]. Thus, relevant process data from the CNC machine, such as vibration or cutting force, cannot be utilized in a closed feedback-loop from the manufacturing process to either design, process planning or quality control. Potential opportunities to improve product design, reduce manufacturing cost or improve delivery time are limited [12].

To enable a bi-directional data communication between CAD/CAM and CNC systems, thus providing opportunities for process data feedback loops, STEP-NC Standard (ISO 14649) has been developed. STEP-NC is an object-oriented interface, fundamentally building on STEP standard (ISO 10303) and feature data models [13]. It contains a wide range of high-level information such as part and feature geometry, process plan description and technology attributes using a vendor independent format. Exemplary prototypes cover indirect implementations where STEP-NC programs are translated into traditional G-Codes, as well as direct approaches, utilizing specialized STEP-NC interpreter and CNC controller enabling bi-directional communication and adaptive process strategies [14]. Various STEP-NC demonstration examples are highlighted in [15]. In [16], a STEP-NC application for part inspection is demonstrated. More recent research also implemented prototypes for STEP-NC to cover additive manufacturing processes [17] or CAPP process data [18].

The different strategies and their major (dis-)advantages utilizing either traditional G-Code (ISO 6983) or STEP-NC (ISO 14649) are illustrated in Fig. 1.

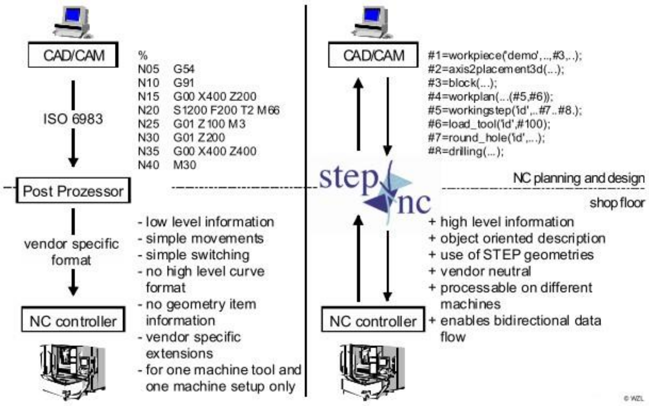

Fig. 1. Comparison of ISO 6983 and ISO 14649 process chain [13].

2.3. STEP-NC closed-loop process monitoring

Based on STEP-NC conform interfaces between CAD/CAM and CNC controls, authors proposed the development of closed-loop control architectures to contextualize gathered process data with high level planning information [19, 20].

In [21] a closed loop STEP-NC architecture is proposed for online feedrate adaption. The author uses the underlaying STEP-NC data model for an optimization module, calculating the new feedrate based on machine feedback [22], highlights the required expansion of STEP-NC functions in order to monitor NC data points. The STEP-NC based planning and scheduling functionality is illustrated in [23]. In [24] the author demonstrates a STEP-NC based closed loop system, connecting CAM and CNC machines using a knowledge database. Additionally, OntoSTEP-NC has been utilized to create an ontology-based knowledge base. Further information is given in [25].

2.4. Summary of state-of-the-art

The described state-of-the-art highlights feature-based data structures as common ground elements for integrated data management in machining process chains. Approaches such as feature-based machining provide relevant information to the CAD/CAM/CAQ chains and support automated generation of the respective NC-code. However, today's CNC systems mostly require the traditional ISO 6983 standard, thus eliminating high level feature information by transforming CAD/CAM planning data into a set of unrelated machine movements. STEP-NC provides a new interface between CAM and CNC to establish a bi-directional and feature-based communication between those systems. Researchers have implemented various STEP-NC prototypes and demonstrated its capabilities in different machining or inspection processes.

Additionally, researchers have focused on the expansion of the underlaying STEP-NC data model in order to provide a generic representation of planning and process information, thus, enabling closed-loop optimization systems.

However, most of the implemented systems are depending on STEP-NC controllers to interpret the specific commands on the CNC machine. While many STEP-NC controller implementations can be found at academic institutes, it seems that industrial use-cases are limited. Heterogenous system landscapes are still a given in the industrial field, hence, limiting the industrialization of these approaches. A hybrid strategy, focusing on establishing an industrial-oriented connectivity layer while utilizing underlaying and standardized feature-oriented data models could support a faster implementation of envisioned closed-loop optimization architectures in the respective industries.

3. System for industry-oriented and bi-directional data exchange for CNC machining processes

This paper presents an industry-oriented approach for automatic and feature-based data collection, enabling technological data analytics for process engineers. In this work, a feature-based data collection system is developed and tested gathering meta and process information from a subtractive process chain considering process planning, process execution, as well as process quality control.

3.1. Concept for feature-based data collection

The system builds fundamentally on ideas for bi-directional data exchange in the CAD/CAM/CNC process chain using design and manufacturing features defined in standards such as STEP or STEP-NC, however, utilizes commercial CAD/CAM software and numerical controls to gather required planning and process data.

In the presented approach, the design and manufacturing feature structure is used as master information element across different steps in the product lifecycle such as virtual process planning, actual manufacturing, and quality control. A feature therefore integrates CAD geometry information (e.g. form and size of the feature, number of faces, edges, design requirements such as tolerances and dimensions.), CAM process planning meta information (e.g. work part meta data, cutting strategies and operations, tool meta data), actual process data gathered from CNC machines and additional sensory systems (e.g. spindle loads, axis positions or vibration sensors) as well as quality control data from equipment such as a coordinate measurement machine (e.g. traditional tolerances and dimensions). Combining all those data sets using the feature structure enables the generation of an advanced feature analytics database, used for automatic and data-driven evaluation and interpretation of optimization potentials in the CNC machining context.

To enable an industry-oriented and flexible approach, the envisioned feature-based data collection system needs to be decoupled from individual software systems used in the CAD/CAM/CNC process chain and act as an intermediate layer between virtual process planning and real machining entities. It needs to provide flexible interfaces to communicate with historically grown system architectures and proprietary formats used within systems of the CAD/CAM/CNC chains.

In this work, a decoupled feature analytics database was implemented and connected to exemplary software and hardware components in the context of CNC machining. In the envisioned system, a feature-based data structure responsible for data collection is implemented on an industrial PC in the CNC environment and provides interfaces for major aspects of subtractive machining and quality measurements. Fig. 2 provides an overview about the envisioned system architecture.

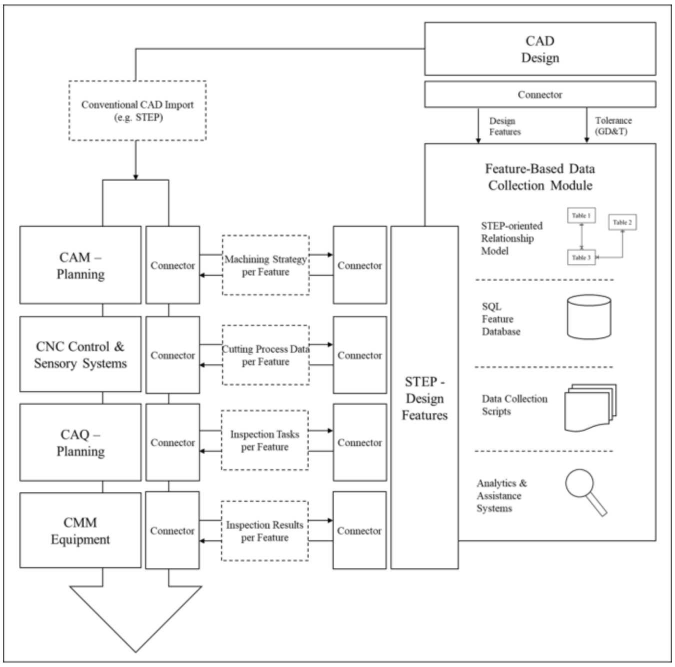

Fig. 2. Concept for Feature-Based Data Collection Module.

The main advantage of the proposed architecture is its flexibility regarding the integration within given industrial software system chains. Compared to approaches such as STEP-NC, which usually requires new CNC controllers, the proposed system acts as a decoupled module, capturing relevant data from various software and control systems by utilizing individual connector points. Once the connector is established, the centralized feature structure of the respective part is used as the main data element across all software systems. Thus, industrial companies can continue using their established software chain but are still benefitting from a feature-based data collection and related analytics. Once a company decides to exchange various software systems, only the connector needs to be adapted/replaced while the data collection functionality remains untouched. The proposed architecture also supports larger manufacturing companies having the need to cope with various historically grown setups, including different machine tools, different control systems and CAD/CAM software tools. Using the proposed system, data from different plants can be collected in a centralized, feature-based module. Hence, more data is combined and can be used for cross-plant analytics.

3.2. Prototype development

The described feature-based data collection module has been implemented as a prototype in the laboratory of TU Wien Pilotfabrik 4.0 in Vienna. The prototype highlights the potential in using a feature analytics platform which integrates various planning, meta and process data from a CNC environment. Following the typical engineering process of the CAD/CAM/CNC chain, the feature-based data collection module gathers process meta data as well as actual machining data from the equipment during production. The prototype design and implementation focuses on three major elements: (a) a feature-based database model, (b) necessary connectors to selected CAx software systems, (c) an interface to the CNC of the used machine tool and (d) the data exchange with the measuring equipment at the end of the process chain.

First, a fitting database for feature-based data collection has been designed and implemented in a selected software environment. The task of the database is to store relevant process planning data, machining process data and respective quality results in a central, feature-based context. For this, a relational database management system was selected (PostgreSQL) and required tables and primary keys have been modelled. The database separates between (a) meta information such as feature structure or machining strategies, (b) timeseries data from the CNC and additional sensor systems integrated in the machine tool as well as (c) final quality measurement data, validating the success of the selected machining strategy for a given feature. For every part, a specific serial number can be entered, linking part individual process data with feature and operation meta information. A schematic overview about the developed database is given as entity relationship model in Fig. 3.

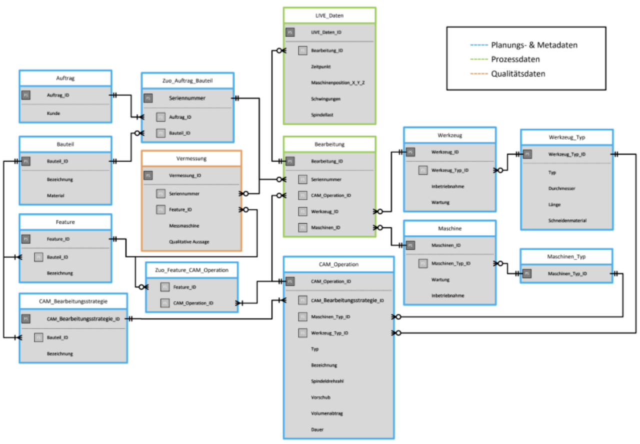

Fig. 3. Entity Relationship Model for Feature-Database.

Second, the feature-based data collection module needs to be interconnected with various CAx software systems. As a first step, the main feature structure for a specific work part needs to be created and exported to the data management application. Such features are typically created by the design and manufacturing engineer in the CAD/CAM environment, requesting an interface to extract relevant feature information into a neutral format. To access required design features and geometrical sub-elements (e.g. faces), *Siemens NX CAD* software and the provided *NX Open Application Programmable Interface (API)* have been used. Additional product manufacturing information such as tolerances can be accessed as well. The data is stored in the developed feature database and can be used as central information carrier along the process chain. Similarly, the *NX Open* interface was used to gather and store respective meta information from the *Siemens NX CAM* module, such as planned operations, utilized cutting tools, cutting parameters or calculated cycle times. To increase the flexibility of the system, all accessed data points are first transformed into a human readable XML format before importing the data sets into the developed feature database for further processing.

Third, while feature-based software support is state-of-the-art in common CAx chains, additional effort on CNC level is necessary. Traditionally, feature information from CAD/CAM environment is lost during the transformation of the planning data into machine interpretable ISO 6983 code ("G-Code"), thus needs to be re-established in order to link relevant process data into similar feature structures. In this prototype, the link between the feature structure and the process data is recovered using unique identifiers defined in the G-code either as commentary lines, or utilizing specific commands (e.g. "MSG-Message" command available on Siemens Sinumerik controls). By adapting the required post processors, feature information key words can be added to every single operation when transforming CAM planning data into G-code. Using this additional information, a data capturing process is able to identify current operations during the process, hence, is able to flag all gathered process data accordingly. For this purpose, a data collection script in python programming language has been developed. Once the G-code is started at a CNC machine, the data collection module activates the python script and starts to gather pre-defined data points from the numerical control (e.g. actual feed, actual spindle speed, override values, axis position) and additional sensor systems using OPC UA and MQTT as communication technology. A similar approach has been chosen to also integrate additional sensor systems. An innovative sensory tool holder system developed at the Institute for Production Engineering and Photonic Technologies, has been setup in the utilized machine tool for cutting vibration measurements close to the cutting zone. The tool holder is connected to an OPC UA server, providing its vibration data to outside systems. Similar to the data gathering using machine tools, the external sensory device provides relevant data that will be added to the respective feature structure by the data collection module.

Fourth, for tactile CAQ inspection planning and respective quality data capturing, *Siemens NX CMM* and the *Dimensional Measuring Interface Standard (DMIS)* have been utilized. NX CMM offers similar functionality as a traditional CAM software, supporting the programmer with functions to plan specific inspection paths for measuring tools. DMIS describes general inspection tasks in a neutral format and is implemented as interface in the Siemens NX CMM environment. Again, the measurement planning data is stored in the developed feature database. Once finalized, measurement results can be exported via DMIS as well.

4. Validation

4.1. Experimental setup

The prototype has been implemented at TU Wien Pilotfabrik Industrie 4.0 in Vienna. Developed software components such as the feature-based data collection scripts are deployed on an industrial EDGE computer, which is connected to the Siemens NX CAD/CAM software systems, and the respective hardware in the laboratory. For the experimental setup, a EMCO Maxmill 500 5-axis CNC machining center with a Siemens Sinumerik 840d sl numerical control has been used. Additionally, an innovative sensory tool holder capable to measure cutting vibrations during milling was integrated into the machine tool setup. For quality measurements, a Wenzel SF87 coordinate measurement machine has been utilized. In order to test the developed feature-based data collection module, a rectangle aluminum workpiece (EN AW 6060, L x W x H: 80x80x30 mm) has been chosen. The final part geometry consists of two simple manufacturing features, a drill hole and a slot, which provides different data to be collected during part design (CAD), operation planning (CAM), actual machining (CNC and sensory tool holder), as well as tactile quality control (CMM). Using the developed system, relevant data sets are gathered, and stored in the feature database for further analysis, thus, the validation of the proposed approach.

4.2. Results

First, data extraction from the CAx software chain was successfully implemented. The geometrical feature information has been designed in Siemens NX CAD environment. Using the NXOpen programming interface and the developed data extraction script, all CAD feature as well as 3D product manufacturing information (flatness, circularity) could be extracted into the feature database. In the process planning stage, relevant manufacturing planning information for the cutting process on the milling machine was defined in Siemens NX CAM. Specific parameters for the slot milling and drilling operation such as machining strategy, cutting parameter, used tooling, and material removal volume were transferred into the feature database using an xml intermediate structure and the NXOpen interface. In a similar way, planned inspection operations from the NX CMM module have been accessed, and relevant parameters such as the feature to be measured, measurement type, number of measurement points or the used tool were imported into the feature-database.

Second, the functionality for feature-based process data extraction from a CNC equipment could be demonstrated successfully. For communication with the milling equipment, OPC UA and MQTT technology has been utilized. The standard Sinumerik OPC UA interface transfers data from the machining center to an MQTT broker, providing a standardized access point for the data management application. The machining center provides data about current spindle load, active tools as well as spindle speeds and feedrate. Additionally, the integrated sensory tool holder system provides information about cutting vibrations measured during slot milling, utilizing similar OPC UA and MQTT infrastructure. The process data is gathered with a sample rate of 200 milliseconds and added to the database.

Third, the integration of CMM measurement data points could not be implemented without manual work. Although the specified flatness of 0,05 for the slot feature, and a circularity of 0,15 for the drilled hole have been measured successfully, the used DMIS interface was not able to transfer all required feature master data from the data collection module to the used *Quartis* measurement software. In the demonstration scenario, the respective feature link has been established manually in order to demonstrate further analysis options.

Lastly, after having stored all relevant data points in the developed feature-database, a first exemplary user interface for data analysis has been established. Using the proposed data collection system, a drill-down from quality related problems, towards technology-oriented data sets is possible. For example, a selected tool can be analyzed based on maximum and minimum cutting vibrations during selected manufacturing orders. Also, a history of removed material per tool and per serial number is possible. A flatness requirement that has not been met can be analyzed using CNC data per machining operation and compared to previous manufacturing orders. Further analyses are possible using the developed feature-based data collection module. Fig. 4 gives an overview about the demonstrator process and a used analysis interface.

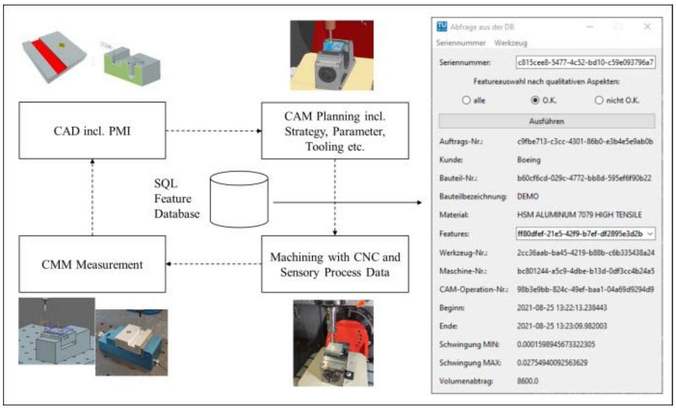

Fig. 4. Data gathering and analysis using developed prototype system.

5. Conclusion and Future Work

This paper presents an industry-oriented approach for machining data management building on the fundamental principle of feature-based design and machining. A flexible, feature-based data collection module is targeted, communicating with various CAD/CAM software systems, machine tools, additional sensor systems as well as measurement equipment using individual interfaces towards the commercial systems.

A prototype for the feature-based data collection module was successfully implemented in a demonstration scenario at TU Wien Pilotfabrik 4.0 in Vienna. Relevant data sets from Siemens NX CAD, CAM as well as CMM could be exported via the available NXOpen API and integrated in the developed feature database. All data sets and respective details are linked via the geometric feature structure defined during part design in CAD. However, tests targeting a direct and automated feature data transfer between the developed system and the CMM equipment failed due to missing alignments within the standardized DMIS format, used in the demonstration scenario. First examples for new opportunities in manufacturing data analytics, using the developed database, have been successfully demonstrated.

Further research is required to support industrialization of the proposed approach. The designed database structure needs further alignment with already implemented STEP and STEP-NC standards. For the communication with the CMM, an industrial postprocessor like the ones of typical CNC machines need to be developed. This will ensure seamless communication and automatic feature-based data collection for measurement data. Lastly, a feature analytics platform shows potentials when combined with machine learning approaches. Here, the specific requirements in regard to algorithm training need to be reflected in the feature structure.

Acknowledgements

This work has been partially supported and funded by the Austrian Research Promotion Agency (FFG) under the contract number 886881 in the project AeroDOM and the TU Wien Pilotfabrik Industrie 4.0, Seestadtstraße 27, Vienna, Austria. The TU Wien Pilotfabrik has been partially funded by the Austrian Research Promotion Agency (FFG) with funds of the Federal Ministry for Transport, Innovation and Technology under contract number 852105.

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