

FRAMEWORK FOR MILLING PROCESS MONITORING

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Modern machining systems use horizontal and vertical data integration for the automatic monitoring and quality control of the machining operations. There are currently available some comprehensive papers focused on high-level system integration. Independently of that, there are also multiple publications focused on the automatic monitoring of specific machining operations. There is lack of presented connections between the high-level proposals and the operation-level methods. This paper proposes a framework for milling process monitoring that covers both mentioned levels, i.e., the system complexity as well as particular operation details. The data model consisting of five key objects (cutting tool management; machine tool; workpiece; machining operation and user) is presented within the framework.

KEYWORDS

machining data framework, machine tool, milling, cutting tool, tool wear monitoring, cyber-physical production systems

1 INTRODUCTION

Modern production is based on complex manufacturing systems. The system complexity means horizontal integration across the production chain and also vertical integration across the production machines and superior monitoring and control layers. The last ten years of development have brought some new ideas for a fusion of the data from real production machines and from the virtual systems for increasing the overall production effectivity. Some comprehensive papers have recently been published on this topic.

[Qu 2019] summarized the state of the art and future trends of smart manufacturing systems (SMSs) development. The paper presents four groups of functions and requirements on SMS: key objectives (autonomous lean operation, sustainable value, win-win partnership), functions (self-sensing, self-adaptive, self-organizing, self-decision), emerging technologies (big data, CPS, IoT, cloud and fog computing, AI, AR, VR, block chain) and business (business planning and logistics, operation management, quality control). With respect to the overview of available technologies, the paper introduces a hierarchical architecture of SMSs' autonomous scheme including the machine layer, control layer, planning layer and execution layer.

[Liu 2018] presented a generic system architecture for cyber-physical machine tools (CPMT). The CPMT structure consists of physical devices connected through the network services with the machine tool cyber twin used for evaluation of the data acquired from the machine. The CPMT is also linked to the data

storage device (cloud device) with implemented big data analytics providing feedback for the product developers and process planners. The paper also presents a simple structure of an MTConnect-based and OPC-UA-based information model of a simple turning machine.

[Tao 2019] presents a study on the correlation and comparison of physical production machines and their digital twins. Based on mapping between physical and cyber/digital worlds in cyber-physical systems (CPS) and digital twins (DTs), a hierarchical model of CPS and DTs in manufacturing is introduced as a mirrored pyramid with three main layers: device layer, system of systems layer and platform layer. The integration of CPS and DTs with new IT is discussed in the paper. At the end, the similarities and differences of CPS and DTs are summarised as is the potential for collaboration of both systems.

[Helu 2020] focused on the distributed production systems. The idea of distributed production is based on the distributed physical assets (production machines, robots etc.) connected through a virtual environment. The five layer system hierarchy is based on ISA-95 standards. As presented in the paper, modern production systems have to be connected with structured data sharing to improve the overall production effectivity.

[Kurfess 2020] provided a review of communication technologies for digital manufacturing processes. The paper presents a systematic overview of connection strategies and frameworks used for various levels of communication, e.g., edge-to-fog connections or fog-to-cloud connections using multiple communication protocols such as OPC-UA, MTConnect and MQTT. Existing methods for manufacturing data acquisition are also presented. Possible applications for manufacturing processes are discussed in the paper.

The mentioned references are focused on the comprehensive systems interconnection. There are also some publications focused on the framework with a focus on the machine tool level and close neighbourhood (edge computation, machine tool digital twin). [Caesar 2020] presented an information model of a digital process twin for machining processes. The model ensures a connection between various technical objects of the manufacturing process: workpiece, machine tool, tool, process planning and digital twin of the process. The model is based on VDI 3682 and was verified on an example of the three axis milling centre. The approach is primarily focused on the machining data processing and evaluation. [Denkena 2021a] proposed a solution of a process chain with monitoring of the machining process supported by historical data of the workpiece. The method was demonstrated on a combination of the forming process and subsequent turning process. [Ganser 2021] proposed a digital twin framework for the machining domain as a domain-specific implementation of a big data lambda architecture combined with the draft ISO 23247. The framework application was presented on the example monitoring the blisk production. [Plahotnik 2021] presented a framework for coupled digital twins in digital machining. The approach connects and combines information based on measured and simulated data for identification of the process critical areas. The solution was demonstrated on the mould milling, including the detection of the worn tool.

The referred papers are focused on the top-level system complexity or propose a particular solution for selected applications. The existing work lacks a wider relation to the process planning and feedback from the process monitoring with respect to the existing state of the technique. The aim of this paper is to connect the top-level view with the specific particular data exchange needed for the planning, monitoring and control of the machining operation. Thus, the paper

proposes a framework for milling process monitoring that covers both mentioned aspects, i.e., the system complexity as well as particular operation details. The paper is organised as follows: all operational tasks related to machining systems are mentioned in section 2. Following the inputs and outputs of this section, the framework is described in section 3. Some application examples are provided within section 4.

2 OPERATIONAL TASK RELATED TO MACHINING SYSTEMS

Modern machining systems need to have information on this specific information used for different purposes: machining system setup and identification; collision avoidance information; cutting parameter settings; workpiece quality demands; cutting tool lifetime and chatter avoidance.

2.1 Machining system setup and identification

The machining system setup means information on the specific machine tool configuration and the specific tool configuration. The machine tool identification is necessary for complete information on machine tool kinematics, performance parameters and working space size. The situation is more complex in the case of the cutting tool. The cutting tool is always composed of a tool holder, modular tool body and the cutting edge represented with a cutting insert or with a monolithic tool. This complete assembly has to be identified with a unique code physically represented by a QR code or RFID technology.

2.2 Collision avoidance

Collision avoidance is one of the critical activities that has to be provided for the successful automatic operation of the machining system. The collision avoidance prediction is challenging on the machine tool with complex kinematics, e.g., on multifunctional centres [Moriwaki 2008]. Recently, the virtual machine tool models have been used for predictive collision avoidance [Altintas 2005] and also for real-time collision avoidance [Schumann 2013]. The key information for these systems is the geometrical envelope of the tool-machine tool-fixture-workpiece system. Thus, the data model of the cutting tool has to involve the geometrical envelope of the current tool setup defined under a unique ID (see section 2.1)

2.3 Cutting condition setting

Nowadays, the initial setting of the cutting conditions is defined by the technologist during the process planning in CAM. The cutting conditions (cutting speed and feed per tooth with respect to the tool engagement conditions) are recommended within some range by the tool producer. The real cutting conditions may vary close to the selected values due to specific process control, e.g. trochoidal milling, speed and feed variation with respect to the tool load etc [Vavruska 2018], [Stejskal 2021]. This varying cutting condition should remain within specified limits respecting the tool design and therefore they have to be also included in the tool data model.

2.4 Chatter avoidance

Chatter is a critical state of the machining operation that should be avoided [Altintas 2004]. For predictive chatter avoidance methods applied during the process planning phase as well as for in-process chatter avoidance strategies [Munoa 2016], the dynamic compliance (FRF) at tool centre point (TCP) is the basic information. The FRF at TCP is different for every tool type and for various machine tool positions in the working space. Receptance coupling substructure analysis (RCSA) [Schmitz 2003], [Park 2003], [Albertelli 2013] is a successful method combining FRF measured at the spindle nose with the simulated dynamic properties of the rotary tool to handle this variable dynamic behaviour during the sequence of machining

operations. Since the rotary tools are modelled using axis-symmetrical beams, the simplified geometrical information about the tool has to be provided. These data can be used also for the collision avoidance analysis, see section 2.2.

2.5 Machining operation monitoring

The machining operation monitoring is an integrated task for production quality control. The process data can be evaluated just on the level of signal processing or using a comprehensive approach based on the cyber-physical system concept [Hänel 2021]. For every processing of the operation data time records, information on the cutting tool, the tool path and the tool-workpiece engagement are important. The primary focus of the machining operation data processing is on the workpiece quality: occurred chatter detection, estimation of possible workpiece deformation [Agarwal 2020], [Denkena 2021b], and estimation of the surface quality. The secondary focus is on the tool condition monitoring: tool wear evaluation e.g., through the change of the specific cutting force [Liu 2022].

3 FRAMEWORK FOR MILLING PROCESS MONITORING

3.1 Framework structure description

The proposed framework is presented at the five parts of Fig.1a – Fig.1e following five main objects: cutting tool management; machine tool including its virtual model; workpiece including its fixture; machining operation and user/operator. Some objects have a child substructure for a more comprehensive description of all the details important for the operation tasks as described in the previous section.

3.2 Tool management

The cutting tool data model structure is presented in Fig 1a. The tool is identified with a unique identifier “Tool_ID”. More descriptions are used for various purposes. The “Duplo” variable is the tool identification within multiple sibling tools (the same mechanical setup of the tool burr of more physical individuals is identified). “Tool assembly description” section provides information on the whole tool assembly e.g., for a quick identification of spare parts. “Weight info” and “Dimension” area describes the main physical parameters of the tool. This is important mainly for manipulation of the tool – check of the non-collision space in the tool magazine and force parameters needed on the side of the tool exchange manipulator. “Collision dimension” provides detailed information about the tool envelope for the collision analysis during the simulation of the machining operation. “Tool life” information is used for planning and monitoring the tool’s remaining useful life. “Actual state” is used for monitoring where the tool is currently placed (specific machine/magazine etc.), its status (active/inactive) and other rather statistical information on the tool usage.

The tool has two substructures. The “edge” structure enables the differentiation of more edges on one tool. This is mainly useful for integrated rotary tools where e.g., the spiral drill and countersink are integrated in one tool. Every edge has a defined outer dimension used for length and radius corrections during tool path calculations. Also, the tool wear limits measurable using the tool probe are defined. For the operation monitoring, vibration and tangential cutting force coefficient limits can be assigned. The dynamic compliance (FRF) for chatter prediction is also defined on the level of the tool edge. The “tooth” substructure involves identification, basic cutting edge parameters, cutting condition setting and limits of engagement conditions for every specific tool tooth. This enables the description of e.g., monolithic tools with variable teeth geometry.

Tool management

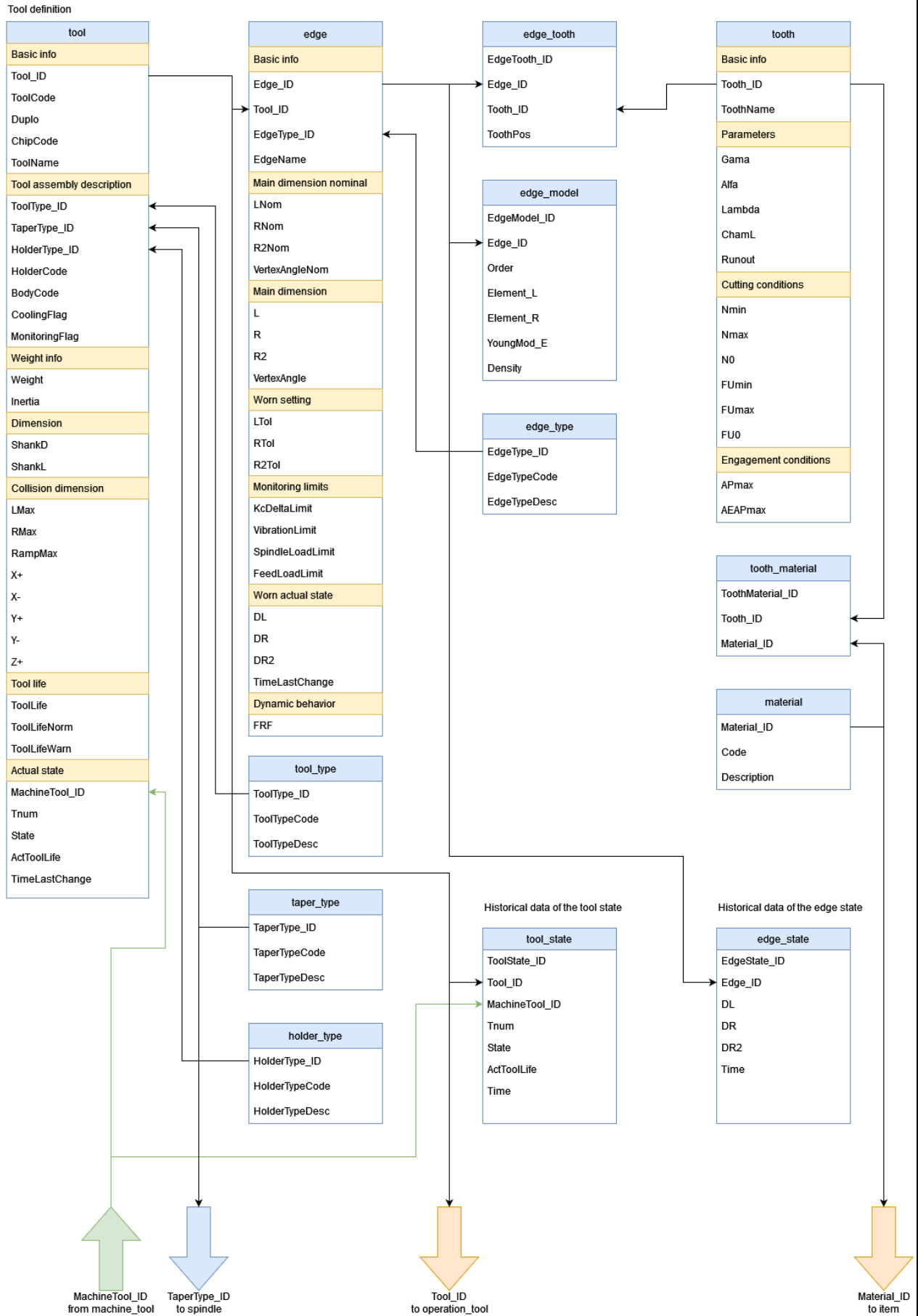


Figure 1a: Schema of the framework for milling process monitoring: the data model for the tool.

Machine tool

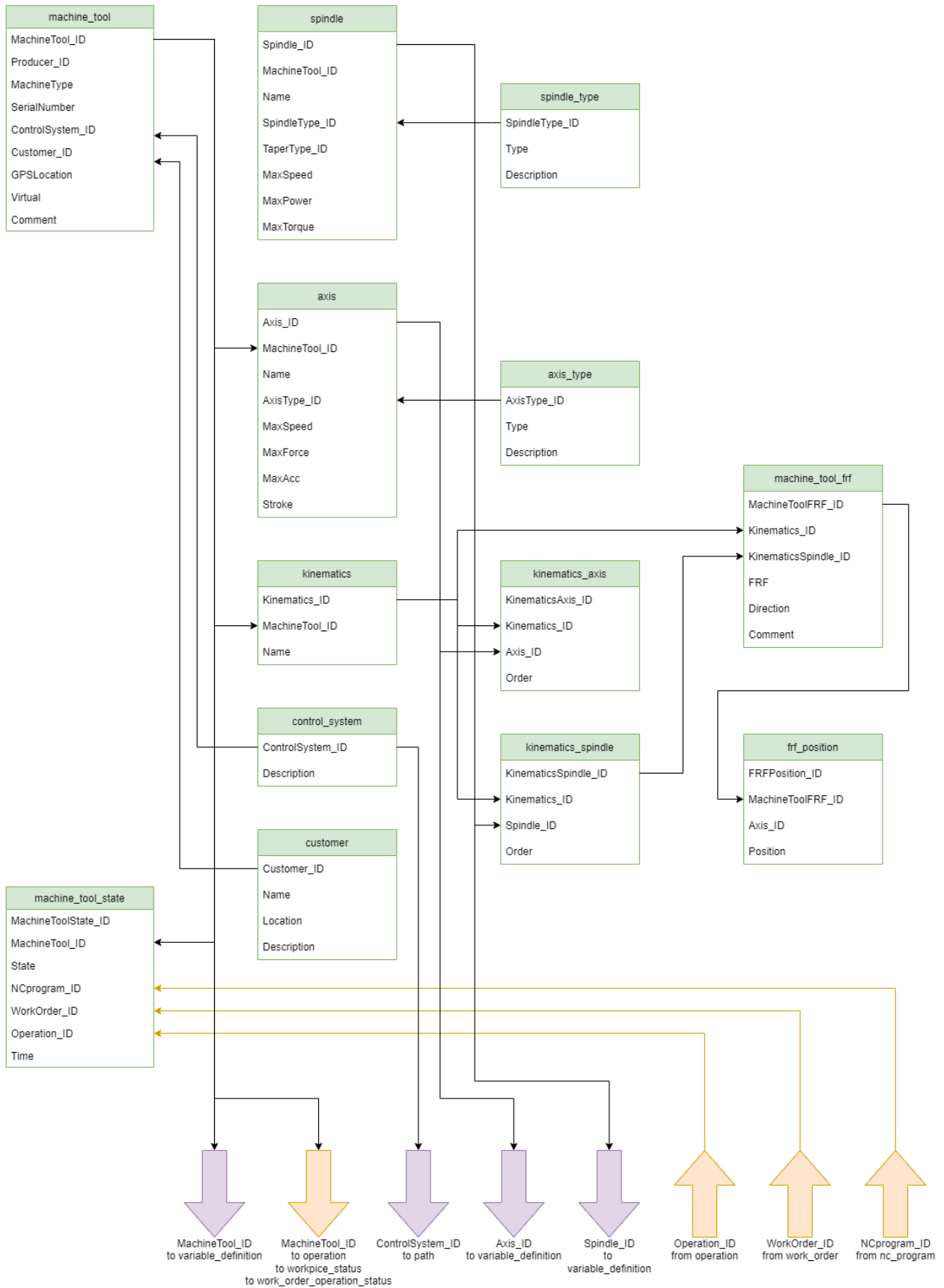


Figure 1b: Schema of the framework for milling process monitoring: the data model for the machine tool.

Workpiece

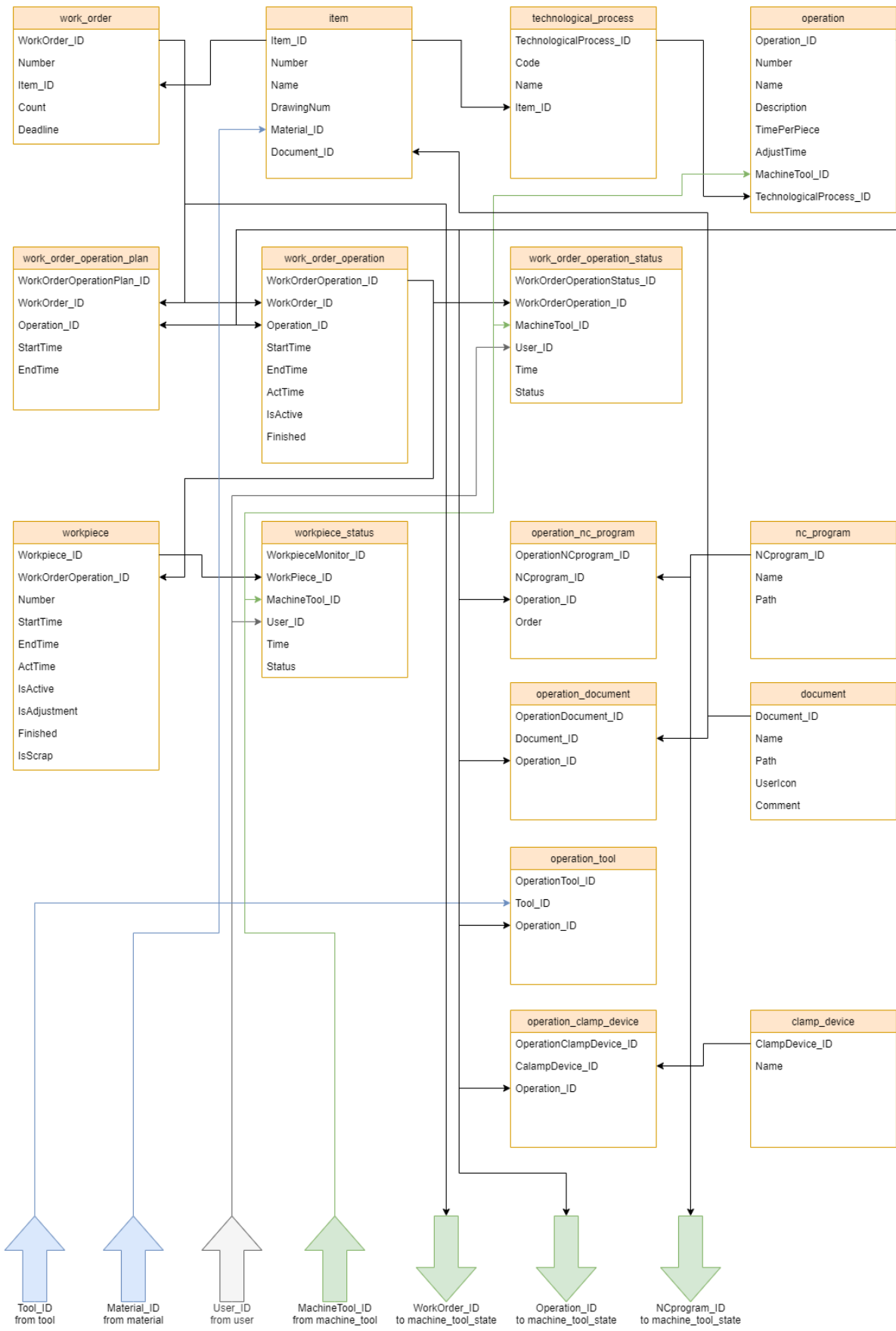


Figure 1c: Schema of the framework for milling process monitoring: the data model for the workpiece.

Monitoring

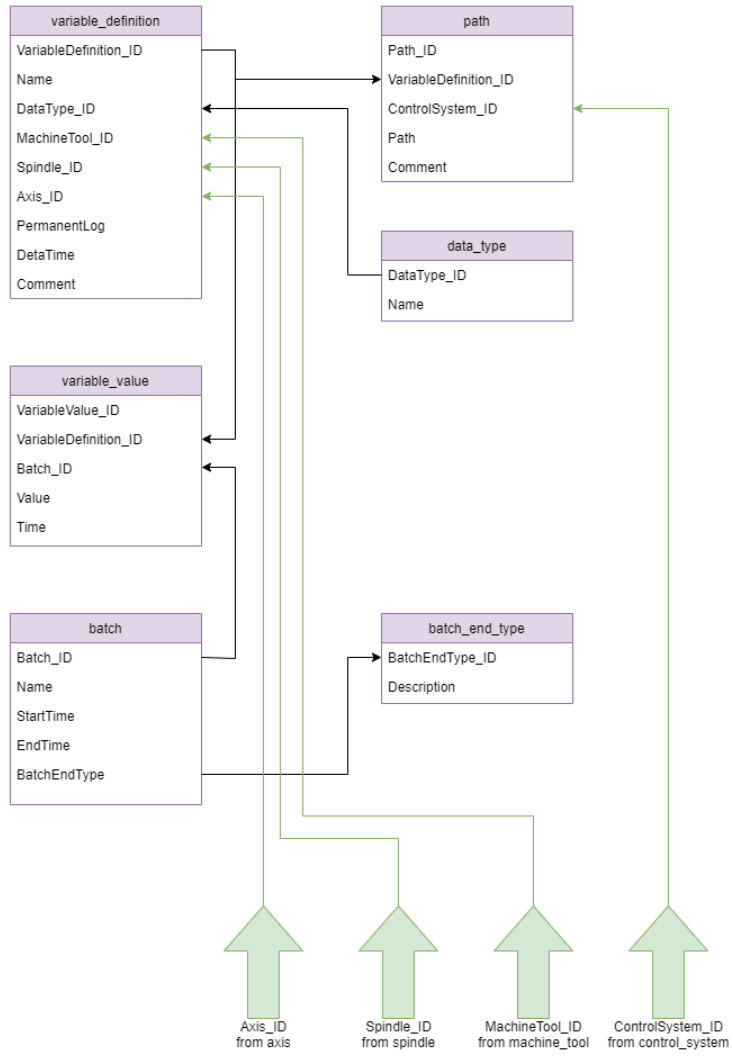


Figure 1d: Schema of the framework for milling process monitoring: the data model for the operation monitoring.

User

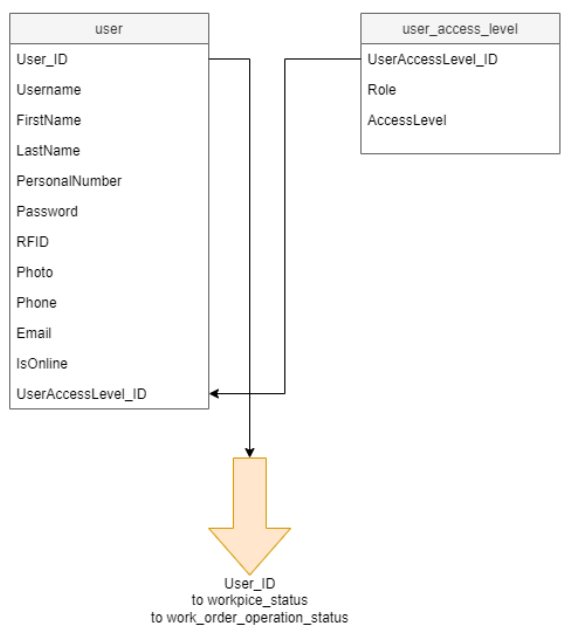


Figure 1e: Schema of the framework for milling process monitoring: the data model for the operator (machine tool user).

3.3 Machine tool

The machine tool data model structure is presented in Fig 1b. The machine tool is defined on the general level by the producer brand and the machine type. This information defines on the basic level the kinematic configuration of the machine tool. On the specific level, the machine tool serial number has to be included. This is important for service-relevant activities. Concurrently, the specific technical parameters of the machine tool spindle or spindle head (revolutions, performance parameters, axes stroke etc) as well as control system type are presented.

The machine tool has three groups of the object child. The first child is the spindle. The specification of the mechanical design and drive performance are the key issues. The spindle compliance is important for the chatter prediction using the predictive digital twin. Please note, that the spindle compliance is included in the whole machine tool FRF within the position-dependent object "machine_tool_fr". The second group of specific objects is the data structure for the description of every movable axis. The third child object is the "control_system" specifying the interpolation abilities of the specific machine tool important for the processing of the recorded data.

The virtual representation of the machine tool is integrated within the main "machine_tool" structure. This so-called machine tool digital twin is a tool for processing the requested and also recorded data from the machine.

3.4 Workpiece

The workpiece object is closely connected with the planning and monitoring of the production, as can be seen in Fig. 1c. Thus, information about the work order and production planning is the dominant volume of this part of the schema. The "item" object involves the production definition of the workpiece by production drawing (or, paperless production documentation) and other documentation, mainly technology planning documentation ("technological_process" and "operation"). The "workpiece" means one specific physical part that is produced, i.e., one item defines more real produced workpieces.

The workpiece has defined data structures enabling the realisation of all planned production operations. There is information on NC programs, specific clamping devices and cutting tools used for the machining.

The status of every workpiece is monitored, including the production time. This information is mainly input to the company ERP system to ensure the online overview of the overall production with respect to the production plan. The time period for the evaluation of this information is usually on the order of minutes.

3.5 Machining operation monitoring

The operation monitoring structure is presented in Fig 1d. As mentioned above, the machining operations should be monitored for in-process and postprocess quality control. For some types of production (e.g., the production of aerospace or space parts [Hänel 2021]) the machining operation monitoring and evaluation is an important theme. The presented data structure enables the definition of the machining operation for monitoring and the monitored data sources (from the machine tool control system or from the external sensors). The monitored data are stored as batches of high frequency data with a typical period of no longer than 5 msec. The data are connected through the "path" object with information of the current tool path and other machine and process setting.

3.6 User

Albeit the ultimate goal of modern production is unattended production, a skilled operator is still a key factor for successfully completing some machining operations. Since the operator can affect the machining quality and performance, it is necessary to have a data structure enabling the user identification and linkage with production under the user's responsibility. See Fig. 1e.

3.7 System connectivity

Except for the machine tool configuration data, other presented data objects have to update their information content regularly. There are differences in the communication period of all objects. The workpiece structure communicates with ERP within a period of a few minutes. The tool management data, the machine tool state and workpiece data are updated on event or with a period of 500 msec, which is the typical period for the subscription of selected variables in the control system. The machining operation monitoring involves various variables with specific monitoring frequency, e.g., high-frequency data on the process are acquired with a frequency of 200 Hz or higher. The vibration data from the accelerometer typically has a frequency of a few kHz.

4 APPLICATION EXAMPLE

In this section, some examples of the framework demonstration are presented and commented on to show how the framework can be applied for typical machining systems.

4.1 Cutting tool management

An example of the cutting tool description within the framework is demonstrated partially in Fig. 2. The tool is composed of multiple bodies ("taper, holder, shank") and can have more cutting edges with a specific tooth number and geometry. The collision envelope of the rotary-symmetric tool can be described using a cylindrical envelope with a defined length and radius. If the tool is not symmetric (e.g., for multitasking turning applications), the envelope can be defined using a non-symmetric block volume with XYZ dimensions.

The tool life can be described using three values: current life time value "ToolLife", total life time value "ToolLifeNorm" and warning time limit "ToolLifeWarn". Also, the status of the tool should be monitored, especially in the large shop floors with shared tool management. The tool can be characterised with the machine tool where "MachineTool_ID" is installed, current position within the machine tool "Tnum", multiple state options, actual tool life time since last change to the spindle.

As presented in Fig. 2, the tool can have more cutting edges "edge" with multiple teeth "edge_tooth". The cutting geometry of every tooth for every edge can be described e.g., for cutting force simulation purposes. The static and dynamic properties of the tool can be modelled as a series of the shaft elements with a defined length and radius and a specific structural material (parameters of "edge_model" structure).

4.2 Machine tool

The machine tool is characterised by its producer, type and unique production number. Information about the customer should also be defined for subsequent service and customer support purposes. If the machine tool is equipped with the spindle head automatic change system, more machine kinematic should be defined. Information on structural properties (dynamic compliance) has to be described within the data model of the machine tool for running digital twin related simulation tasks. See an example for a specific machine in Fig. 3.

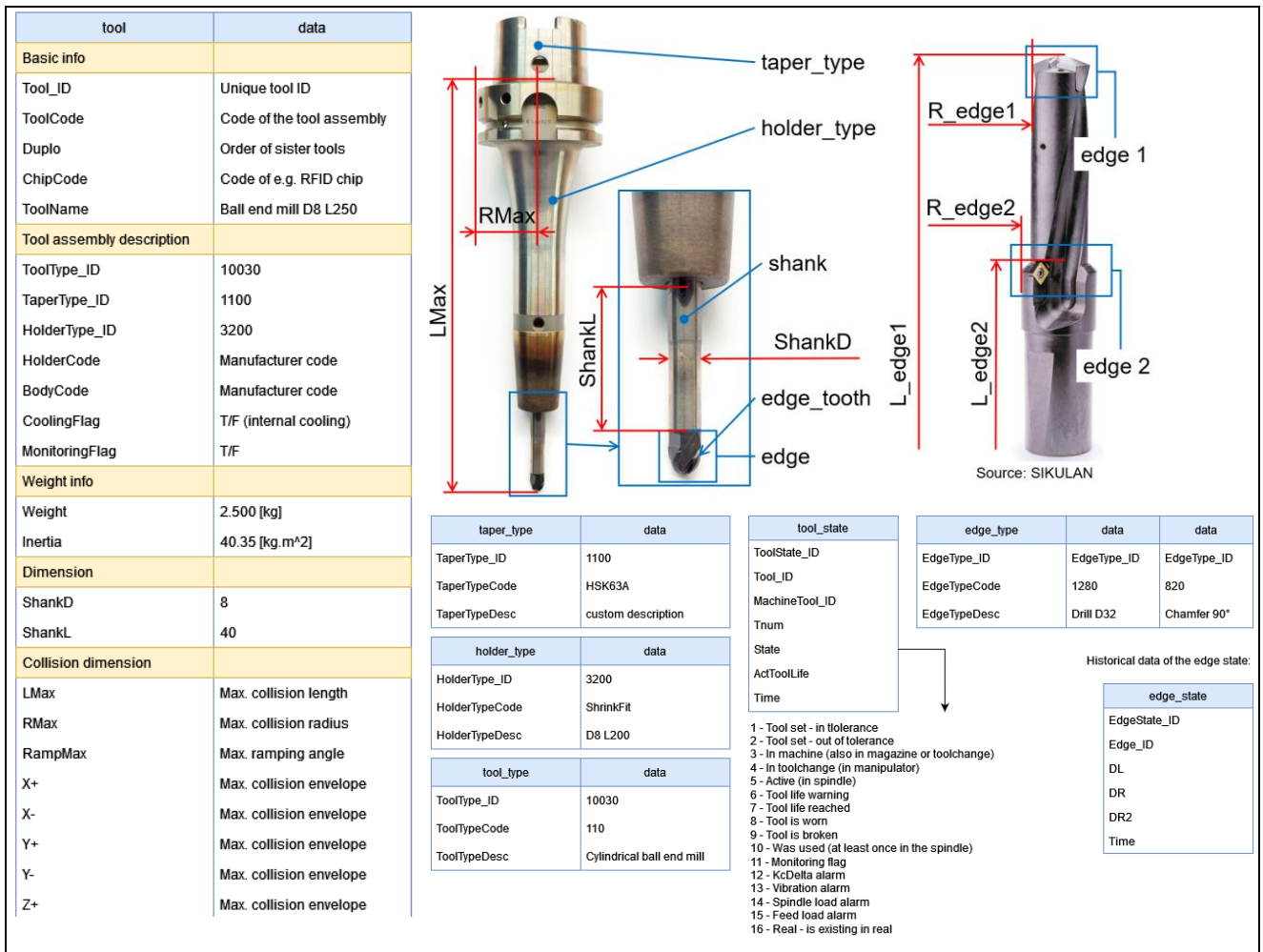


Figure 2: Example of the cutting tool components and their description within the proposed framework.



Figure 3: Example of the cutting tool data model components and their description within the proposed framework.

work_order		item		technological_process		document	
work_order	data	item	data	technological_process	data	document	data
WorkOrder_ID	758085	Item_ID	35626	TechnologicalProcess_ID	11622	Document_ID	258963
Number	01150046	Number	V060186700	Code	TP000008296	Name	SPINDLE LID
Item_ID	35626	Name	SPINDLE LID	Name	060186700 SPINE	Path	null
Count	10	DrawingNum	V060186700	Item_ID	35626	UserIcon	LID.jpeg
Deadline	2022-07-14	Material_ID	Material_ID			Comment	NO COMMENT
Document_ID	258963	Document_ID	258963				

work_order_operation		work_order_operation_status		operation		work_order_operation_plan	
work_order_operation	data	work_order_operation_status	data	operation	data	work_order_operation_plan	data
WorkOrderOperation_ID	422449	WorkOrderOperationStatus_ID		Operation_ID	257690	WorkOrderOperationPlan_ID	159357
WorkOrder_ID	758085	WorkOrderOperation_ID	422449	Number	1010	WorkOrder_ID	758085
Operation_ID	257690	MachineTool_ID	MachineTool_ID	Name	WHT110	Operation_ID	257690
StartTime	2022-07-04 00:00:01	User_ID	User_ID	Description	MACHINING	StartTime	2022-07-04 00:00:01
EndTime	2022-07-07 00:00:01	Time	Time	TimePerPiece	10	EndTime	2022-07-07 00:00:01
ActTime	2022-07-06 00:00:01	Status	Status	AdjustTime	0		
IsActive	1			MachineTool_ID	14		
Finished	0			TechnologicalProcess_ID	11626		

workpiece		workpiece_status		operation_document		operation_tool	
workpiece	data	workpiece_status	data	operation_document	data	operation_tool	data
Workpiece_ID	1122262	WorkpieceMonitor_ID	987456	OperationDocument_ID	741963	OperationTool_ID	OperationTool_ID
WorkOrderOperation_ID	422449	WorkPiece_ID	1122262	Document_ID	258963	Tool_ID	Tool_ID
Number	null	MachineTool_ID	14	Operation_ID	257690	Operation_ID	257690
StartTime	2022-07-04 06:58:2	User_ID	User_ID				
EndTime	2022-07-04 07:11:5	Time	2022-07-04 07:11:57				
ActTime	2022-07-06 00:00:01	Status	0				
IsActive	0						
IsAdjustment	0						
Finished	1						
IsScrap	0						

nc_program		operation_clamp_device		operation_nc_program		clamp_device	
nc_program	data	operation_clamp_device	data	operation_nc_program	data	clamp_device	data
NCprogram_ID	321456	OperationClampDevice_ID	951753	OperationNCprogram_ID	426531	ClampDevice_ID	357
Name	Q_060186700_C	CalampDevice_ID	357	NCprogram_ID	321456	Name	BASIC CLAMP
Path	null	Operation_ID	257690	Operation_ID	257690		
				Order	Order		

Figure 4: Example of the workpiece data model components and their description within the proposed framework.

4.3 Workpiece

The framework part related to the workpiece involves information about the workpiece itself and about its production process (material, geometry, manufacturing operations). Every machining operation needs a definition of the NC code, specific clamping device and used tools. See the example in Fig. 4.

4.4 Machining operation

Various technical effects, such as chatter occurrence detection or tool wear monitoring can be analysed if multiple machine tool variables are monitored (see the example in Fig. 5). For a time record analyse for the decision making, it is necessary to store the requested operation parameters as well as many additional meta data needed for the time record processing and understanding of the results.

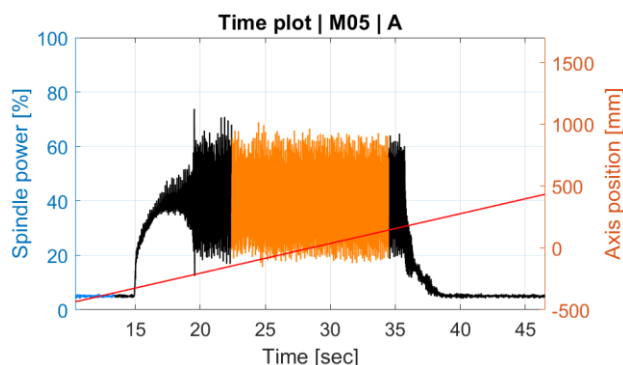


Figure 5: Example of the specific machining operation monitoring – a time-domain plot of spindle power and X axis position.

5 CONCLUSIONS

The paper presents the data structure of a framework for milling operations. The framework has five main parts: cutting tool management; machine tool; workpiece; machining

operation and user. The defined structure and connection between objects enables the realisation of high-quality machining operations with automatic data acquisition for in-process and postprocess quality control. The framework is generic. We can expect that in the future, some parts of the presented data will be provided by the component supplier as a digital twin of the physic product.

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