

HSM2025-44991

CRITICAL ASPECTS OF PRACTICAL IMPLEMENTATION OF DIGITAL TWINS IN MACHINING

Matej Sulitka^{1*}, Jiri Falta¹, Michal Rytir^{1,2}, Albrecht Hänel³,
Guanchen Gong³, Petr Kolar^{1,2}

¹Czech Technical University in Prague, Faculty of Mechanical Engineering,
Department of Production Machines and Equipment (RCMT, FME CTU in Prague)

²Czech Technical University in Prague, Czech Institute of Informatics, Robotics and Cybernetics,
Department of Industrial Production and Automation (IPA CIIRC)

³Fraunhofer Institute for Machine Tools and Forming Technology (IWU)

*Corresponding author; e-mail: m.sulitka@rcmt.cvut.cz

Abstract

Process digital twins are developed for predictive checks and optimisation of machining processes and for post-process checks of workpiece quality based on machining data. Although there are significant advantages to applying both of these concepts, practical implementation is difficult and hindered by various barriers. This study presents a use case of mould milling on a medium-sized machining centre supported by predictive and post-process digital twins. The study includes quantification of machining errors as well as possible steps for improving the process in terms of workpiece surface quality and machining productivity. Issues related to incorporating digital twins into the process planning workflow are described and a resultant hybrid digital twin (HDT) concept is proposed. The HDT consists of predictive and post-process parts, both in the minimal viable configuration. The predictive digital twin includes a CNC interpolator for simulating the set-point position values and machining time. The post-process digital twin includes a material removal model based on CNC actual feed drive positions which makes it possible to compare programmed and actual workpiece geometry, enabling quick identification of surface errors. The approach is demonstrated and verified on the mould milling use case.

Keywords:

Hybrid Digital Twin, Mould Machining, Predictive Machining Process Simulation

1 INTRODUCTION

Digital twins are emerging as one of the key technologies driving process digitalisation. With the advancement of sensor technology and communication capabilities integrated into CNC control systems, machining processes have become a significant source of large volumes of data. Effective processing and utilisation of this data, especially when combined with simulation models, provide a basis for potentially more effective process planning and control—ultimately enhancing productivity, reliability and product quality. Digital twins play an increasingly significant role among these digital solutions.

While the term "digital twin" lacks a universally accepted definition, it is generally understood as a virtual representation of a physical object, enriched with data and information that enable the synchronisation between the physical and digital counterparts. The concept was first introduced by Grieves in 2002 in the context of product lifecycle management (PLM) [Grieves 2014]. The International Academy for Production Engineering (CIRP) defines a digital twin in the following way: "A digital twin is a digital representation of an active unique product (real device, object, machine, service or intangible asset) or

unique product service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions and behaviour employing models, information and data within a single or even across multiple life cycle phases" [Stark 2019]. Earlier work by both Onosato and Iwata demonstrated how virtual manufacturing systems could integrate product models with factory models to simulate and optimise manufacturing operations at a system level [Onosato 1993], [Iwata 1995]. Such approaches laid the groundwork for digital twins that extend beyond single machines or processes toward holistic representations of entire manufacturing systems.

In the machining domain, a digital twin is characterised by Negri et al. as "a virtual representation of a production system that is able to run on different simulation disciplines and is characterised by the synchronisation between the virtual and real system, thanks to sensed data and connected smart devices, mathematical models and real-time data elaboration" [Negri 2017]. Similarly, Bergs et al. describe a digital twin as a "virtual representation of the physical state of real objects or systems, whereby these real objects can change their state" [Bergs 2021]. A fundamental and shared feature of digital twins is the integration of data and models that bind together virtual and physical products, enabling the prediction of system behaviour in real time. Within the domain of machining, this

integration begins with the virtual representation of the machine tool itself.

The virtual representation of the machine tool lies at the core of machining-oriented digital twins. The early development of such models involved coupling finite element models of machine mechanics with drive dynamics and control loops [Berkemer 1997], [Zatarain 1998], [Zäh 2004], [Denkena 2002]. Altintas and Brecher demonstrated that virtual machine models are essential not only for virtual testing and shortening of development cycles, but also for simulation of machining processes [Altintas 2005] and for integrated simulation of machine, process and workpiece [Brecher 2005]. Coupled models of structural dynamics and drive systems enable prediction of a machine dynamic behaviour and identification of control parameter limits with respect to the mechanical design [Maj 2005], [Vesely 2009], and the coupled simulation of machine dynamics and control loops [Weck 2003]. Lin [Lin 1996] emphasised the importance of CNC interpolator functionality and trajectory planning capability, while Erkorkmaz and Altintas proposed a method for tuning drive control parameters using a virtual machine model [Erkorkmaz 2001a, b, c], and through Hardware-in-the-Loop techniques enabling real-time testing of control systems [Pritschow 2004].

A virtual model of a machining process is based on material removal simulation, which allows for the computation of tool engagement conditions and force interactions among the tool, workpiece and machine. Workpiece volume representation strategies prioritise either geometric resolution or computational efficiency [Altintas 2014], with common approaches using discrete line segments (depth pixels – dexels) or volumetric elements (voxels), which serve as the basis for simulations that enable both prediction of tool engagement and visualisation of surface quality and machining errors. The signed distance function method in particular is able to achieve high visual fidelity [Sulitka 2022].

Force interaction models between the tool and workpiece are typically based on mechanistic force models, incorporating tool engagement geometry and local force integration along the cutting edge [Montgomery 1991], [Altintas 2005]. Force prediction is essential both for roughing operations, where spindle load profiles are of interest, and for finishing thin-walled components, where the objective is often process optimisation to minimise deflection or prevent chatter [Altintas 2008]. In recent years, digital twin technologies have made it possible to link force models directly with virtual machining simulations. This means cutting forces can be predicted in real time based on planned tool paths and machining parameters, without relying solely on measurements [Hänel 2019], [Hänel 2021]. These models enhance early detection of possible process limits and allow for adjustments before actual machining. Moreover, combining force models with machine dynamics models improves predictions of vibration behaviour and stability, which is important for high-speed machining in particular [Brecher 2009]. These advancements support digital twin applications by simulating machining operations and helping to optimise them.

These technological developments form the basis for practical applications of digital twins in machining. Therefore, this article presents a use case of mould milling on a medium-sized machining centre supported by a hybrid digital twin (HDT) that combines predictive and post-process components. The HDT includes a CNC interpolator for simulating toolpath and machining time, and a material removal model based on actual CNC feed drive positions to

identify surface errors. The modular system uses MATLAB/Simulink, OPC-UA communication between the CNC controller and process simulation, and supports both pre-process verification and post-process evaluation of machining results. The use case highlights challenges in practical implementation and demonstrates the potential for improving process planning and surface quality.

2 BUILDING THE DIGITAL TWIN

This chapter describes the layered structure of a digital twin (DT) used for the analysis and evaluation of machining processes, particularly in high-speed operations. It explains the type of information provided by each layer and how it can be used during process planning, simulation, execution and quality assessment. In this chapter we differentiate predictive use (before machining) from post-process use (after machining), as well as data obtained from simulation, machine sensors and part measurements.

The first layer is the programmed toolpath, represented by cutter location (CL) data exported from the CAM system. These data define the geometric trajectory of the tool centre point (TCP), feed rates and tool orientations. However, they do not take into account machine dynamics or control system behaviour. This level is suitable for initial verification of the machining strategy and for path visualisation. In practice, errors in CL point distribution can occur due to limitations in CAM algorithms or incorrect assumptions in strategy design. Simulations using CL data can help detect such issues early, before actual machining takes place.

The second layer consists of position setpoints, which are the output of the CNC interpolator. These signals are sent to the servo drives and reflect the effect of active control features such as look-ahead, filtering and corner rounding. In our study, we focused on the effect of Cycle 832, which influences path smoothness and dynamic performance in high-speed cutting. These position setpoints form the basis of the predictive digital twin, enabling realistic assessment of motion accuracy, smoothness and achievable productivity. This layer is important for comparing strategies in terms of geometry and dynamic machine behaviour.

The third layer includes the actual positions of the machine axes, provided either by encoders, or direct measurement by linear scales. Data from linear scales are recorded during machining and reflect the actual machine tool response, including effects such as drive performance, delays and disturbances. This information is used in the post-process digital twin to compare programmed and actual motion, detect deviations and support fast quality checks. These data can in turn also be combined with the machine tool virtual model, which includes simplified models of the structure and drives, to perform pre-process evaluations.

Another important layer is the estimation of the real TCP position. Since the TCP cannot be measured directly during machining, it must be calculated using either a rigid kinematic model or a dynamic model that includes structural and tool compliance. The latter is typically based on finite element analysis (FEA), providing a more realistic prediction of the actual motion of the cutting point. This level is important for evaluating surface quality and dimensional accuracy. At this stage, the simulation considers only inertial effects and does not take into account process forces. Namely, cutting forces become important mainly when predicting machining performance, or when significant deflections between the cutting tool and workpiece occur in the process.

A further, more advanced layer, which we call process level digital twin, includes modelling of process forces and the interaction between the machine, tool and workpiece (Figure 1). Although this level is not always used in practice, it is useful for simulating process stability (chatter), predicting the deflection of flexible parts and evaluating the influence of cutting forces on tool behaviour. It can also support fixture design and process sequence planning. Incorporating process forces into the digital twin improves the quality of predictions, particularly in demanding or precision applications.

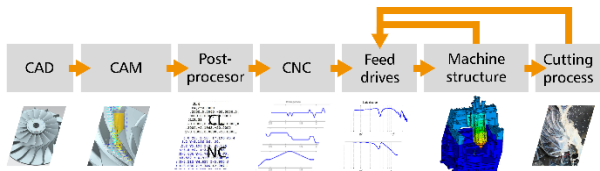


Figure 1: Scheme of the full process level digital twin

This approach allows for systematic analysis of machining behaviour. Each layer provides different insights, from early CAM strategy validation to real-time comparison with machine data. The structure supports the identification of surface error sources and selection of appropriate corrections, such as adjusting control settings, changing toolpaths or compensating for structural influences. Leveraging information from multiple layers increases the reliability of process planning and may reduce the need for a detailed part inspection. A digital twin that integrates toolpath, CNC interpolator output, structural compliance and cutting forces offers a consistent framework for predicting and improving machining performance.

The study performed within this article considers both the predictive and post-process digital twin. The predictive digital twin includes machine tool and feed drive coupled virtual model (Figure 2), therefore we call this level as “Machine tool level predictive digital twin”. Machine tool structural dynamic properties are represented by finite element model (FEM), which is subject to modal reduction and transformation into state space. In state space, force coupling with ball screw drives mechanics is established and implemented into a feed drive cascade control model.

The coupled virtual model provides TCP positions, based on which material removal simulation and machined surface visualisation is performed. MillVis software, developed by RCMT, is used for this task.

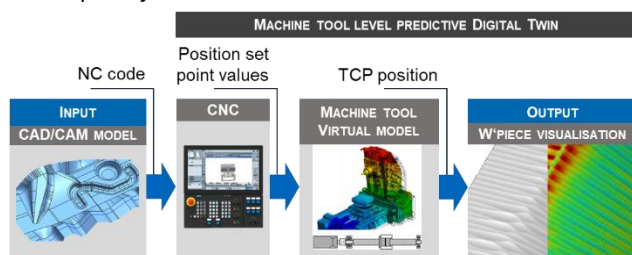


Figure 2: Scheme of the machine tool level predictive digital twin

Machine tool post-process digital twin, employing Sinumerik EDGE for reading the CNC position actual values (by feed drive linear scales), is introduced in more detail in Chapter 5. Scheme of the model presents Figure 3.

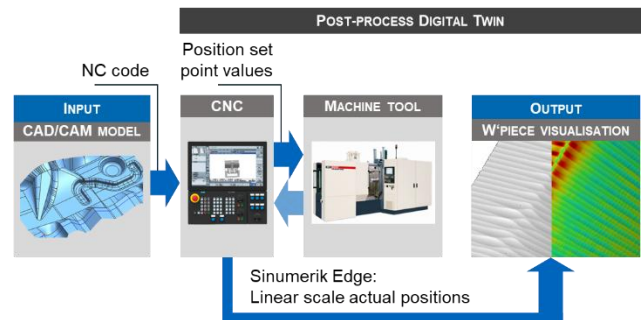


Figure 3: Scheme of the machine tool post-process digital twin

3 OVERVIEW OF MOULD MILLING USE CASE

The following chapter provides a detailed overview of the test part, machining equipment and strategies applied in the experiment. Emphasis is placed on the semi-finishing operation, which serves as the focal point for evaluating digital twin integration in terms of productivity and machining accuracy.

3.1 Workpiece description

The milled part is a mould insert designed for injection moulding applications (see Figure 4). It features a combination of free-form and prismatic surfaces, including inclined planes, oval-shaped protrusions and rounded internal corners. The part's geometry is characterised by two circular pockets and several sharp-edged transitions. The overall shape includes sloped walls and shallow cavities, representing realistic toolpath transitions and surface orientation changes typically encountered in mould production. The minimum corner radius of the forming features is 5 mm, which influences the selection of cutting tools. The part was machined from a C45E steel blank with dimensions of 260 × 250 × 60 mm.

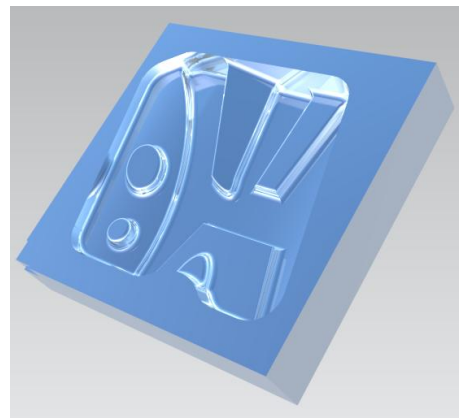


Figure 4: CAD model of the mould used for the digital twin demonstration.

3.2 Machining system

Machining was performed on a Tajmac-ZPS H630 horizontal machining centre (Figure 5). This machine is equipped with linear X, Y and Z axes (750 × 700 × 770 mm) and a rotary table (B axis, 360°). The feed rate in the linear axes is 50 m/min, with acceleration up to 5 m/s². CNC controller used is Sinumerik 840D sl. The machine provides positional accuracy of 0.008 mm and repeatability of 0.005 mm, making it suitable for high-precision mould machining and integration with digital twin applications.

Cutting conditions, material removal rates and force feedback from simulations were analysed to validate the digital twin model. The simulated spindle power was compared with real measurements to assess the tool's impact on process dynamics and machine load.



Figure 5: Tajmac-ZPS H630 horizontal machining centre

3.3 Overall Machining Strategy

The overall machining process consisted of three stages: roughing, semi-finishing and finishing.

Roughing: In this phase of the process, two cutting tools were applied and tested using the digital twin framework. Evaluation focused on their efficiency and compatibility with high-speed strategies and system limitations. The first tool was a 16-mm diameter end mill with four cutting edges (4-flute), designated MM EFF160T5R3.25-4T10. The second tool used in this phase was a 40-mm diameter indexable cutter with six teeth, designated 40A06R-S90TN10-C. It was optimised for bulk material removal with a lower cutting speed ($200 \text{ m}\cdot\text{min}^{-1}$) and higher axial depth of cut ($a_p = 3 \text{ mm}$). The radial engagement was set to 16 mm. This configuration provided high stability during deep cavity roughing and reduced machining time to 19 minutes. Both strategies aimed to efficiently remove bulk material and maintain stable cutting forces. The digital twin was used to simulate and compare spindle power consumption for each strategy. The simulated values were validated using measurements acquired via Siemens Edge, and the resulting data were used to estimate cutting force model coefficients. A comparison of measured and simulated spindle power provided by the virtual process simulation in SW MillVis, developed at the Czech Technical University (CTU), was conducted after compensating for passive losses.

Semi-finishing: Semi-finishing was conducted in two stages using medium-sized ball-end mills with different axial depths of cut. The operation aimed to remove the remaining stock after roughing and to ensure geometric stability before finishing. All strategies used a cutting speed of $300 \text{ m}\cdot\text{min}^{-1}$. The CAM tolerance was set to $\pm 0.03 \text{ mm}$, aiming to ensure accurate surface replication. An ISCAR MM EB100A07-4T06 ball-end mill with a nominal diameter of 10 mm, four cutting edges, a 30° helix angle and a maximum allowable axial depth of cut of 7 mm was used for these operations. A Fixed Contour strategy was applied with a toolpath orientation of 45° . Detailed tool parameters and cutting conditions for both semi-finishing passes are provided in the corresponding table. Emphasis was placed on evaluating and optimising this step.

Finishing: A small-diameter tool with fine step-over was used to achieve high surface quality. This step improves surface roughness but cannot correct macro-geometric deviations. The machining parameters, including tool paths,

feed rates and step-over values, were optimised to balance productivity and surface quality. It is important to note that the roughing strategy had a direct impact on the quality and effectiveness of the semi-finishing operation due to variations in stock allowance.

Therefore, this study focuses on the semi-finishing operation, where machining errors are still visible and productivity considerations (such as larger step-over values) are more relevant than in the finishing step. The goal is to evaluate and improve this operation using both predictive and post-process digital twins, as discussed in the following sections.

4 DETAILED ANALYSIS OF SEMI-FINISHING OPERATION

The effect of different Cycle 832 settings on machining time, geometric accuracy and surface quality was evaluated using the digital twin. Cycle 832 is a Siemens-specific control function that adapts machine dynamics to the machining objective. It offers a configurable balance between precision and productivity by adjusting parameters such as acceleration limits, jerk control and path smoothing. While roughing modes favour faster movements and reduced machining times, finishing modes prioritise contour accuracy and minimise path deviations.

Understanding and predicting the impact of these settings through the digital twin helps identify the optimal strategy for semi-finishing operations. By evaluating the effect of enabling Cycle 832 on the same roughed workpiece, this study demonstrates how predictive simulation can support the comparison and optimisation of control strategies prior to machining. Such virtual evaluations enable informed decision-making without the need for repeated physical trials.

4.1 Predictive process simulation

The first application of the predictive digital twin was to compare the programmed (CAM) machining time with the actual machining time. The programmed feed rate for the semi-finishing operation was $4700 \text{ mm}\cdot\text{min}^{-1}$. However, this rate cannot be fully realised due to the dynamic limitations of the feed drives, structural compliance and the kinematic constraints of the CNC system.

Two variants of interpolation settings were tested: with and without activation of Cycle 832 (Figure 6). For both variants, the CAM software estimated a machining time of 20 minutes. In reality, the measured machining time was 23.4 minutes without Cycle 832 and 22.9 minutes with Cycle 832 on. This represents an increase of 17% and 14%, respectively, compared to the programmed CAM machining time.

These differences illustrate the necessity of digital twin-based simulations for more realistic estimation of machining times. The influence of interpolation and motion dynamics is especially significant in high-speed semi-finishing, where trajectory smoothing and control loop parameters directly affect the achievable feed rate and motion continuity. Additionally, the system is subject to machine-specific limits on axis acceleration and jerk, which further restrict the execution of nominal feed rates in complex toolpaths.

The digital twin was also used to visualise surface deviations introduced at different stages of the digital process chain—from CAD geometry to the final machined part. Based on simulated or measured structural dynamics, the digital twin generates spatial maps of predicted surface errors. These maps reflect deformation effects caused by structural compliance and drive behaviour during high-

speed motion. Importantly, by comparing intermediate stages in the process chain, the digital twin makes it possible to identify which step contributes most significantly to the final surface deviation—whether it is the CAM strategy, CNC interpolation or machine dynamics. This enables identification of specific surface regions where geometric deviations are likely to occur, supporting targeted inspection or further process refinement.

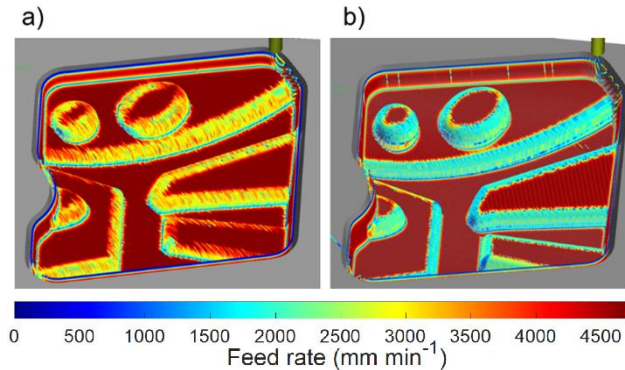


Figure 6: Feed rate distribution resulting from Cycle 832 activation – Smoother toolpath transitions with Cycle 832 allow faster machining a) Cycle 832 ON, b) Cycle 832 OFF. Notice the higher feed rates at radius segments with Cycle 832 ON.

In the first step, the study focused on the effect of the selected CAM strategy during the generation of cutter location (CL) points. The density and distribution of these points significantly influence the smoothness of the resulting toolpath after interpolation, which in turn affects surface accuracy and the occurrence of local geometric errors. Examples of such errors during raster machining are highlighted in two regions in Figure 7.

The error in region A was caused by the sparse distribution of CL points during raster machining of curved surfaces. This leads to non-uniform scallop spacing, causing visible variations in surface quality due to the linear interpolation assumptions. The error in region B resulted from using a constant horizontal step-over. On surfaces nearly parallel to the toolpath direction, excessive spacing can occur between adjacent passes. This happens because the projection of the toolpath onto shallow or inclined surfaces leads to an effective step-over that is significantly larger than intended. As a result, surface coverage becomes sparse, leading to visible artifacts, inconsistent scallop heights and potential loss of surface accuracy. To mitigate these effects, adaptive step-over control or surface-normal-based toolpath generation should be considered.

Another layer of error arises from postprocessor settings used to generate CNC code. The interpolation-related error is further influenced by the configuration of the CNC system, particularly the use of Siemens Cycle 832. Cycle 832 allows the programmer to define a preference between surface quality and productivity by specifying geometric tolerance and smoothing parameters. Based on these inputs, the postprocessor adjusts the velocity profiles and position setpoints along the toolpath. Consequently, the same CL point data can produce different machine behaviour depending on the selected cycle mode, potentially leading to surface deviations in areas with

complex curvature or abrupt directional changes. The cycle distinguishes between machining stages (e.g., roughing, semi-finishing and finishing), each of which can be further refined by enabling optional functions such as TOP_SURFACE or ADVANCED_SURFACE. These options activate different levels of look-ahead filtering, feedforward compensation and axis coordination optimisation. ADVANCED_SURFACE in particular enables enhanced trajectory smoothing, machine-specific tuning parameters and better handling of short vector segments, making it suitable for high-precision applications.

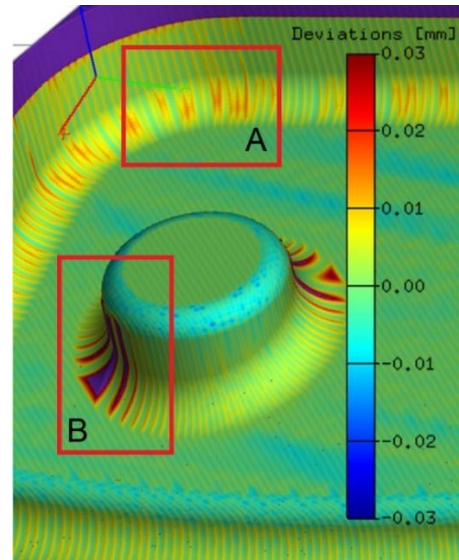


Figure 7: Visualisation of surface approximation errors based on CL points. A: Errors in corner radius due to sparse distribution of CL points in parallel toolpaths, B: Step-over inconsistency on near-parallel regions

In this study, Cycle 832 was activated with ADVANCED_SURFACE settings and a geometric tolerance of ± 0.05 mm. However, surface deviation maps (Figure 5) revealed specific areas where the desired tolerance was not met, indicating that the actual motion execution did not fully conform to the programmed specifications. Increased deviation observed in certain regions was likely caused by a sparse distribution of CL points. In particular, when the tool radius coincides with the form corner radius, only a single CL point may be placed in the critical corner region (see Figure 8, graph III). While this might seem sufficient from a purely geometric standpoint, it poses a challenge for the controller in maintaining local tolerance requirements. Cycle 832 likely evaluates geometric accuracy over segments comprising multiple consecutive points, which can lead to tolerance violations at isolated CL points.

As illustrated in Figure 8, even a slight increase in the corner radius on the opposite side of the cavity (graph I) results in generation of more CL points. This denser distribution enables the controller to approximate the programmed shape more accurately and remain within the defined tolerance.

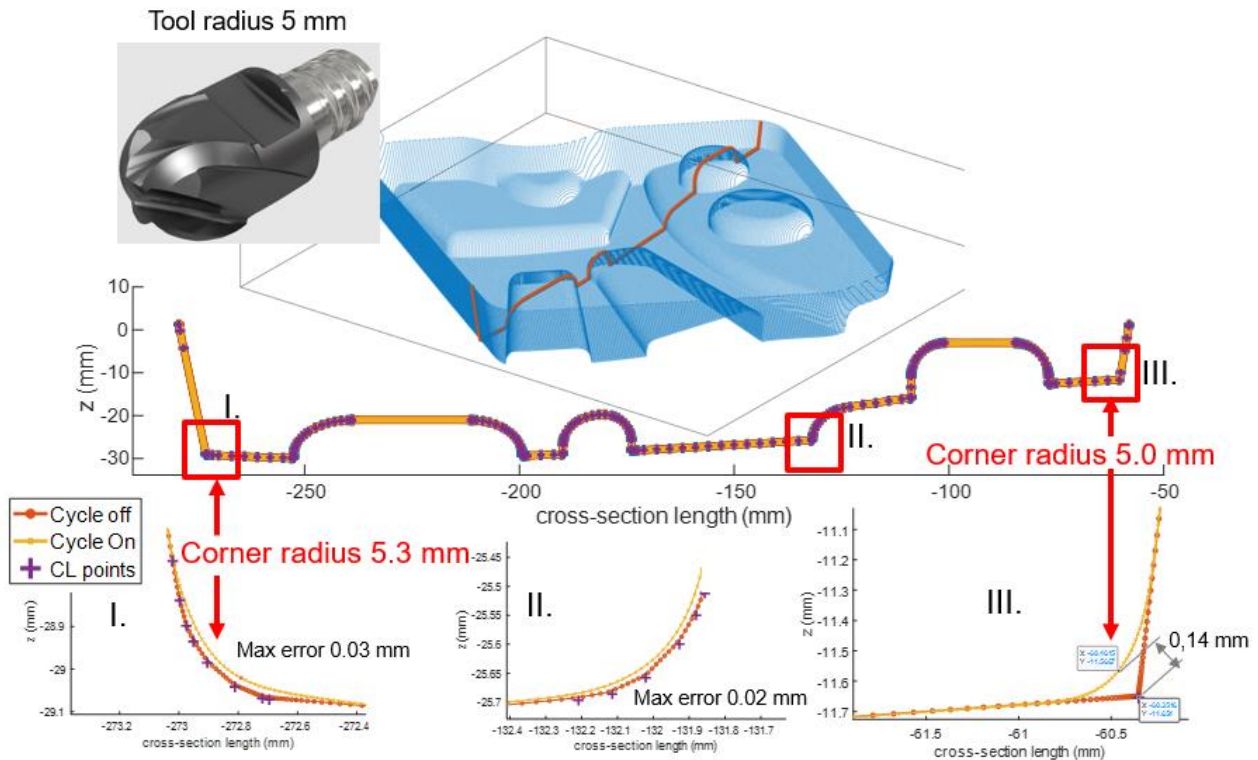


Figure 8: Illustration of CL point distribution along a single toolpath row and its effect on position setpoints with Cycle 832 enabled. Graphs I, II and III show radius transitions where sparse CL point spacing may occur, potentially resulting in setpoint distributions that do not meet the specified geometric accuracy.

Figure 9 further illustrates this effect by showing surface deviation maps generated from the set point geometry and CL-based toolpath. These maps highlight how trajectory deviations introduced by the NC interpolator propagate to the final surface geometry. For the case with Cycle 832 enabled, regions corresponding to toolpath segments II and III are clearly marked, demonstrating localised form errors resulting from insufficient guidance in the trajectory smoothing process.

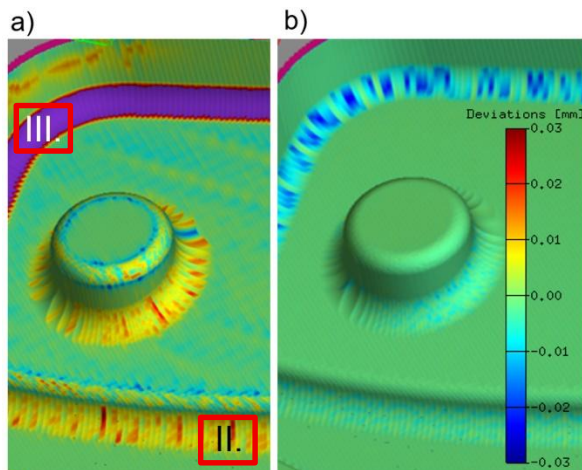


Figure 9: CNC interpolation errors – deviation between the surface defined by CNC position set point data and CL points. a) Cycle 832 ON: Local tolerance violations are visible in zones II and III, which correspond to the critical toolpath regions identified in Figure 7, b) Cycle 832 OFF

The maps of errors in Figure 10 compare the surface generated by the NC-interpreted trajectory with the actual position scale readings. These maps reveal the

discrepancies introduced by drive dynamics, control delays and structural deflections during real-time tool path execution. While the deviations are typically small in finishing operations, they become more pronounced in high-speed segments or complex curvature areas. The maps also show that smoother toolpaths generated using Cycle 832 significantly reduce these deviations by easing dynamic loads on the drives and minimising excitation of structural vibrations.

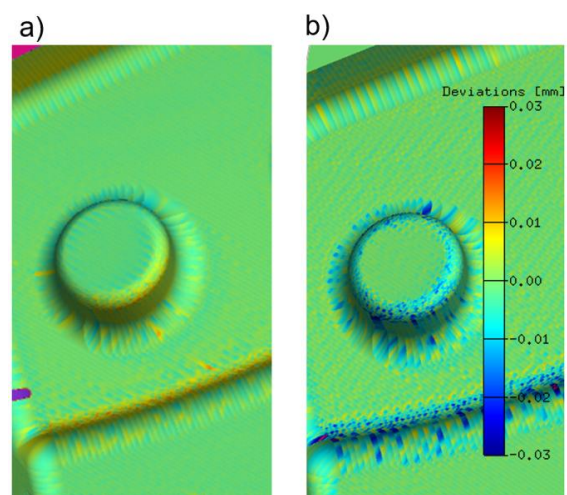


Figure 10: Deviation between CNC position set point data and actual positions from the machine level digital twin; a) Cycle 832 ON, b) Cycle 832 OFF

Impact of feed drive and machine tool dynamics for both the Cycle 832 ON and OFF options is analysed by comparing the deviations between the surface errors generated based on CNC set-point position values and actual feed drive

positions from the machine level digital twin (*Figure 10*). It may be seen, that on shape transition faces the variant with Cycle 832 OFF reveals lower surface quality, however still within the defined tolerance of ± 0.05 mm.

4.2 Real process results

A detailed comparison of the simulated predictions and actual machined surfaces reveals both qualitative and quantitative consistencies, as well as localised discrepancies. In the region of the internal corner radius, the surface profile obtained using Cycle 832 shows a pronounced geometric deviation, closely matching the simulation results. This correlation indicates that the deviation stems from the dynamic limitations of the machine tool during rapid bidirectional changes in tool movement—limitations not fully compensated, even by the advanced kinematic control embedded in Cycle 832. Comparison of machined surfaces when Cycle 832 is ON, or OFF provides *Figure 11*.

Furthermore, in areas machined using a zig-zag strategy, subtle mismatches between adjacent toolpaths give rise to periodic surface irregularities. These artifacts are likewise reproduced in the simulated surface morphology, confirming the ability of the digital twin to capture toolpath induced texture variations and the influence of machine kinematics on surface generation.

Despite these localised deviations, the remaining surface regions exhibit a clear improvement in surface quality when Cycle 832 is activated. Both the simulated and actual surfaces demonstrate reduced surface roughness, the absence of chatter marks and improved continuity in the toolpath imprint. This improvement is primarily attributed to the trajectory smoothing and dynamic feed rate optimisation implemented by Cycle 832, which collectively reduce acceleration-induced excitation and mitigate abrupt toolpath transitions.

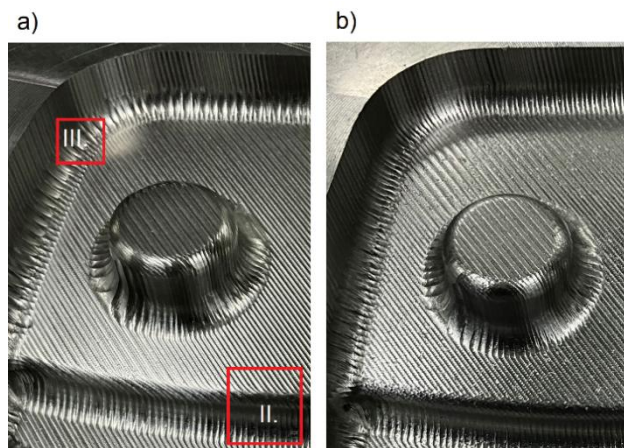


Figure 11: Comparison of machined surfaces a) Cycle 832 ON, b) Cycle 832 OFF

These findings confirm the digital twin capability to predict critical surface deviations caused by machining processes and to assess the functional benefits of adaptive control cycles. The observed alignment between the simulation and experiment validates the model and underscores its usefulness for process planning, evaluating control strategies and predicting surface quality in high-speed mould machining.

5 POST-PROCESS DIGITAL TWIN

In the context of this study, acquiring high-resolution process data is essential. Various high-speed signals—such

as TCP position, drive currents and actual feed velocities—may be collected. These data are gathered from the numerical control (NC) system during machining operations.

To enable this, a SIEMENS Sinumerik EDGE device was deployed within the machine tool. This device operates as an embedded industrial PC (IPC) integrated into the machine control cabinet. It establishes a dedicated interface with the CNC system, allowing real-time data acquisition without introducing latency or interfering with the control kernel. The system supports a sampling rate of up to 500 Hz (2 ms) and enables synchronous monitoring of up to 100 NC channels.

Collected datasets are stored in JSON format, initially written to the local memory of the EDGE device. Application on IPC stores the collected data and provides them to following analysis. Subsequently, the data are transmitted to a cloud-based infrastructure, providing secure storage, remote access and further processing capabilities. This architecture offers a robust framework for monitoring machining processes and supports detailed post-process analyses aimed at process optimisation and model validation.

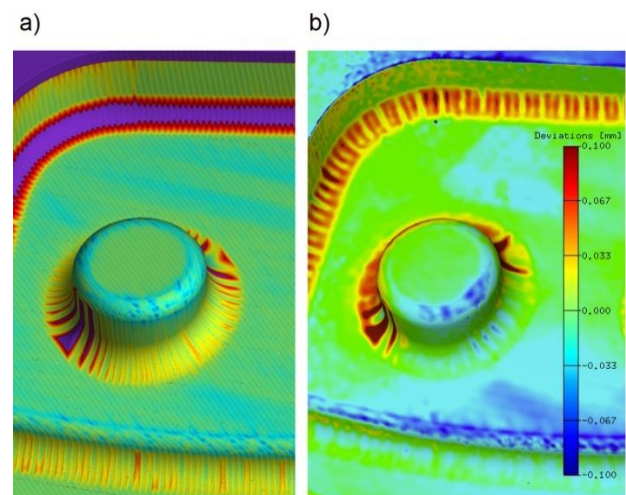


Figure 12: Comparison of post-process digital twin surface error visualization a) and a scan of a real part b), both referenced to the CAD model, Cycle 832 ON. The 3D scan is processed using best-fit alignment. Simulation and scan indicate a good overall match. More specifically, a big error on the internal corner radius (left and upper part of the image), caused by sparse interpolation with Cycle 832, is confirmed on the real surface.

The acquired datasets were further employed for validation of the post-process digital twin by comparing linear scale data based simulation with the geometry of the produced part. High-resolution 3D surface scan of the machined workpiece was obtained using GOM ATOS Capsule with 12 Mpx sensor. As illustrated in *Figure 12*, the map of surface errors provided by the post-process digital twin correlates well with the scan of the real part. More specifically, surface form deviation observed on the internal corner radius corresponds to the error predicted by the simulation, which originates from using Cycle 832 when interpolation points are distributed too sparsely. Both approaches indicate that this trajectory-induced imperfection is directly reflected on the final surface, confirming the correspondence between predicted and measured surface quality and demonstrating the potential of the post-process digital twin for model validation and process analysis.

6 DISCUSSION

This study demonstrated the feasibility of using a predictive and post-process digital twin to assess the semi-finishing milling process on a mould part. The predictive digital twin is a CNC level, meaning no machine tool structural model or machine-process force interaction is considered. A compact medium-sized machining centre is represented by the digital twin.

Two main findings may be drawn from the study:

(1) The machine tool level of the predictive digital twin represents a relevant tool for analysing the NC tool path control for a medium-sized compact machining centre. This is supported by comparing the pre-process predictions—based on CNC interpolator set point values and machine tool virtual model—and post-process simulations—based on encoder data, whereby the discrepancy between the surface error distribution for both of the simulation results is relatively small. This suggests that for such machines, digital twin simulations performed in the planning phase can serve as a reliable and practical tool for process planning and optimisation.

(2) The effect of Cycle 832 on machining time and surface error was investigated using the predictive digital twin. Cycle 832 produces significantly smoother feed rate profiles, which can help reduce dynamic excitation and surface errors, particularly in machines with lower structural stiffness. The smoothing is achieved by relaxing the requirement for exact point-to-point sequence and instead optimising motion within a defined geometric tolerance band. As a result, the controller is able to generate more continuous axis trajectories with fewer abrupt accelerations and direction changes, enabling faster and more stable tool motion without compromising the specified accuracy limits. This behaviour is particularly advantageous in regions with gentle curvature or redundant toolpath points, where local trajectory optimisation can be performed without violating form requirements. On concave surfaces with smooth curvature, the feed rate achieved with Cycle 832 was observed to be up to 50 % higher compared to the baseline setting, highlighting its ability to exploit favourable geometry for improved kinematic efficiency.

In the studied case, this behaviour led to local deviations that exceeded the programmed tolerance, particularly in areas with sparsely distributed CL points. The low point density in these regions resulted from the fact that the tool radius matches the nominal surface radius; consequently, a single CL point was sufficient to geometrically define that portion of the surface. However, such minimal representation can be inadequate for effective trajectory smoothing, as it provides insufficient guidance for the algorithm. This underscores the importance of pre-process analysis, which can identify such issues—such as critical under-sampling of the toolpath—prior to actual machining.

The analysis also revealed that the tolerance specified in Cycle 832 is not enforced pointwise but rather over a segment of the toolpath. The geometric deviation is interpreted statistically or in terms of segment-wise deviation, rather than as a strict envelope constraint.

More broadly, the digital twin must be applied with a clear understanding of its intended role: the predictive model supports pre-process planning, while post-process evaluation aids in interpreting the results. Real-time data acquisition, for example through Siemens Edge, serves as a valuable bridge between the virtual and physical domains; however, its benefit depends on precise modelling and reliable sensor data. Further research should focus on

integrating force models and extending the approach to less rigid machine tools.

7 SUMMARY

The use of a digital twin in milling enables detailed evaluation of surface quality without the need for physical machining, allowing users to identify potential risks and inefficiencies early in the planning phase. By simulating toolpaths and machine behaviour, different machining strategies can be tested and compared in terms of surface finish, tool load and cycle time—without the cost and time associated with physical trials.

Moreover, the digital twin provides a framework for analysing the impact of each element in the digital manufacturing chain, from CAD design and CAM programming to machine tool execution. This end-to-end traceability makes it possible to pinpoint the root causes of geometric errors and systematically improve each stage.

Importantly, predictive simulations reveal not only nominal outcomes but also potential deviations caused by machine behaviour. As shown in the case study, CNC interpolators may not always reproduce programmed trajectories accurately in regions with critical curvature, particularly when trajectory smoothing is applied using control functions such as Cycle 832. The study also demonstrated that if the tool radius matches the local surface radius—as in the case of a ball-end mill with R5 cutting a concave R5 surface—the resulting low point density can lead to local form deviations despite correct CAM output. On a structurally rigid machine, however, the predicted and measured axis positions remained in close alignment, confirming that trajectory-level digital twin models can be used reliably in such conditions. The study was performed on a machine equipped with Sinumerik 840D sl CNC controller, however the principles may be generalized to any other type of CNC controller.

In summary, the digital twin establishes a powerful virtual environment for evaluating, optimising and validating machining processes. It enables informed decision-making based on machine-specific behaviour and helps prevent geometric inaccuracies that arise from the interplay between toolpath design, tool geometry and control strategy.

8 ACKNOWLEDGMENTS

This work was supported by the European Union as part of the project RICAIP “Research and Innovation Centre on Advanced Industrial Production” funded by the EU’s Horizon 2020 research and innovation program under grant agreement No. 857306 and co-funded by the EU through project CZ.02.1.01/0.0/0.0/17_043/0010085. This work contributes to the sustainability of project CZ.02.1.01/0.0/0.0/16_026/ 0008432 Cluster 4.0 - Methodology of System Integration financed by European Structural and Investment Funds and Operational Programme Research, Development and Education via Ministry of Education, Youth and Sports of the Czech Republic. The contribution of the Ph.D. student involved in the team of authors was also supported by the Grant Agency of the Czech Technical University in Prague, grant no. SGS24/129/OHK2/3T/12. The authors would like to thank Matěj Pešice for his support with the preparation of CAM programs and Vojtěch Matyska for his assistance with the virtual machine simulation.

9 REFERENCES

- [Altintas 2005] Altintas, Y., Brecher, C., Weck, M., Witt, S. (2005). Virtual Machine Tool. *CIRP Annals*, 54(2), 115–138.
- [Altintas 2008] Altintas, Y. (2008). Chatter Stability of Milling in Frequency and Discrete Time Domain. *CIRP Journal of Manufacturing Science and Technology*, 1, 35–44.
- [Altintas 2014] Altintas, Y., Kersting, P., Biermann, D., Budak, E., Denkena, B., Lazoglu, I. (2014). Virtual Process Systems for Part Machining Operations. *CIRP Annals*, 63(2), 585–605.
- [Bergs 2021] Bergs, T., Gierlings, S., Auerbach, T., Klink, A., Schraknepper, D., Augspurger, T. (2021). The Concept of Digital Twin and Digital Shadow in Manufacturing. *Procedia CIRP*, 101, 81–84.
- [Berkemer 1997] Berkemer, J. (1997). Simulation von Werkzeugmaschinen unter Berücksichtigung der Antriebsregelung. In: *Tagungsband XXIV. FEM-Kongress, Baden-Baden*.
- [Brecher 2005] Brecher, C., Broichhausen, K.-D., Flegel, H., Fleischer, J., Friedrich, D., Herrscher, A., Klocke, F., Lung, D., Marczinski, G., Queins, M., Raedt, H.-W., Steffens, K., Wagner, P., Willms, H., Witt, S. (2005). Integrierte Simulation von Prozess, Werkstück und Maschine. In: *Tagungsband 25. Aachener Werkzeugmaschinen-Kolloquium*, pp. 307–350.
- [Brecher 2009] Brecher, C., Esser, M., Witt, S. (2009). Interaction of Manufacturing Process and Machine Tool. *CIRP Annals*, 58, 588–607.
- [Denkena 2002] Denkena, B., Tracht, K., Rehling, S. (2002). Simulationsmodul für Maschinendynamik im Rahmen eines Fertigungssimulationssystems. *WT Werkstattstechnik online*, 92, 223–225.
- [Erkorkmaz 2001a] Erkorkmaz, K., Altintas, Y. (2001). High Speed CNC System Design. Part I: Jerk Limited Trajectory Generation and Quintic Spline Interpolation. *International Journal of Machine Tools and Manufacture*, 41(9), 1323–1345.
- [Erkorkmaz 2001b] Erkorkmaz, K., Altintas, Y. (2001). High Speed CNC System Design. Part II: Modelling and Identification of Feed Drives. *International Journal of Machine Tools and Manufacture*, 41(10), 1487–1509.
- [Erkorkmaz 2001c] Erkorkmaz, K., Altintas, Y. (2001). High Speed CNC System Design. Part III: High Speed Tracking and Contouring Control of Feed Drives. *International Journal of Machine Tools and Manufacture*, 41(11), 1637–1658.
- [Grieves 2014] Grieves, M. (2014). Digital Twin: Manufacturing Excellence through Virtual Factory Replication. *White Paper*, 1, 1–7.
- [Hänel 2019] Hänel, A., Wenkler, E., Schnellhardt, T., Corinth, C., Brosius, A., Fay, A., Nestler, A. (2019). Development of a Method to Determine Cutting Forces Based on Planning and Process Data as Contribution for the Creation of Digital Process Twins. *MM Science Journal*, November, 3148–3155.
- [Hänel 2021] Hänel, A., Seidel, A., Frieß, U., Teicher, U., Wiemer, H., Wang, D., Wenkler, E., Penter, L., Hellmich, A., Ihlenfeldt, S., Liang, S. Y. (2021). Digital Twins for High-Tech Machining Applications—A Model-Based Analytics-Ready Approach. *Journal of Manufacturing and Materials Processing*, 5, Article 80.
- [Iwata 1995] Iwata, K., Onosato, M., Teramoto, K., Osaki, S. (1995). A Modelling and Simulation Architecture for a Virtual Manufacturing System. *CIRP Annals*, 44(1), 399–402.
- [Lin 1996] Lin, R. S., Koren, Y. (1996). Real-Time Interpolators for Multi-axis CNC Machine Tools. *Journal of Manufacturing Systems*, 25, 145–149.
- [Maj 2005] Maj, R., Bianchi, G. (2005). Mechatronic Analysis of Machine Tools. In: *9th SAMTECH Users Conference, Paris, France, 2–3 February 2005*.
- [Montgomery 1991] Montgomery, D., Altintas, Y. (1991). Mechanism of Cutting Force and Surface Generation in Dynamic Milling. *Journal of Engineering for Industry*, 113(2), 160–168.
- [Negri 2017] Negri, E., Fumagalli, L., Macchi, M. (2017). A Review of the Roles of Digital Twin in CPS-based Production Systems. *Procedia Manufacturing*, 11, 939–948.
- [Onosato 1993] Onosato, M., Iwata, K. (1993). Development of a Virtual Manufacturing System by Integrating Product Models and Factory Models. *CIRP Annals*, 42(1), 475–478.
- [Pritschow 2004] Pritschow, G., Röck, S. (2004). Hardware in the Loop Simulation of Machine Tools. *CIRP Annals*, 53(1), 295–298.
- [Stark 2019] Stark, R., Damerau, T. (2019). Digital Twin. In: Chatti, S., Tolio, T. (eds.) *CIRP Encyclopedia of Production Engineering*, pp. 1–8. Berlin, Heidelberg: Springer.
- [Sulitka 2022] Sulitka, M., Kolar, P., Sveda, J., Smolik, J. (2022). Strategy for Implementing Predictive Process-Oriented Machine Tool Digital Twins. *MM Science Journal*, October 2022.
- [Vesely 2009] Vesely, J., Sulitka, M. (2009). Machine Tool Virtual Model. *MM Science Journal*, December, 146–152.
- [Weck 2003] Weck, M., Queins, Q., Brecher, C. (2003). Coupled Simulation of Control Loop and Structural Dynamics. *Annals of the German Academic Society for Production Engineering*, 10(2), 105–110.
- [Zäh 2004] Zäh, M. F., Oertli, Th. (2004). Finite Element Modelling of Ball Screw Feed Drive Systems. *CIRP Annals*, 53(1), 289–293.
- [Zatarain 1998] Zatarain, M., Lejardi, E., Egana, F. (1998). Modular Synthesis of Machine Tools. *CIRP Annals*, 47(1), 333–336.