OPTIMIZATION OF FIVE-AXIS FINISH MILLING USING A VIRTUAL MACHINE TOOL

PETR KOLAR, MATEJ SULITKA, VOJTECH MATYSKA, PETR FOJTU

Czech Technical University in Prague, Research Center of Manufacturing Technology, Prague, Czech Republic

DOI: 10.17973/MMSJ.2019_12_2019037

e-mail: p.kolar@rcmt.cvut.cz

Five-axis finish milling is a complex process. The requested surface quality and accuracy must be produced in the shortest possible time. The three main process characteristics - quality, accuracy and machining time - are closely related one to each other. They are affected by the dynamic properties of the machine tool structure, the feed drive properties including cascade control, the control system interpolator properties and the NC code. Thus the appropriate optimization of all related parameters throughout the entire chain is demanding in terms of both time and material. This paper describes the creation of a virtual machine tool that takes into account the properties of the machine structure, feed drives and their cascade control. This machine tool model is connected to the CNC control system kernel. Tests used to verify control system functionality are presented. A virtual simulation of the process is demonstrated on the use case. The process chain parameters are optimized using the virtual machine tool to increase productivity. The simulation and experimental results are compared.

KEYWORDS

Five-axis machining, finishing milling, virtual machine tool, milling accuracy, interpolator, control system, machining productivity, surface quality

1 INTRODUCTION

Five-axis finish milling process is one of the most complex milling operations. The requested surface high quality and accuracy must be produced in the shortest possible time. The three main process characteristics - quality, accuracy and machining time - are closely related one to each other.

The final surface quality parameters depend on the potential of the machine tool structure and the machine control to follow the tool path requested by the NC code. Cutting forces in finishing machining are usually low and do not play an important role in final surface accuracy. The cutting media is important to ensure a cut without any negative effects on the workpiece surface even for small chip thickness.

Altintas and Brecher [Altintas 2005] referred to the virtual machine tool (or alternatively, the machine tool digital twin) as a key tool for virtual testing of machine tools and machining processes. Since modern machine tools are complex mechatronic systems, a virtual machine tool must be able to describe the behaviour of the machine tool structure including the feed drive mechanical structure and control, the control system function and the interaction between the machine tool and the cutting process. These machine tool digital twins can be used for virtual testing and optimization of machine tool design and also for virtual process planning and optimization.

The scope of this paper focuses on the application of machine tool virtual model in five-axis finishing milling of complex parts and the demonstration of the potential of machining process virtual testing and optimization. Finishing machining is characterized by typical application of ball end cutters and small chip thickness. The key issue of process optimization is related to processing (interpolation) a large NC code by the control system and the potential of the machine tool to follow the requested movement commands. Thus, setting of the CNC control system parameters with respect to the interaction between the feed drive control and the machine tool structure plays an important role in achieving high productivity and quality of the machining process.

The concept of virtual production was presented during the 1990's [Onosato 1993], [Iwata 1995]. These concepts were at the manufacturing system level. The authors described the data flow between all related objects. The machine tool was only one of these objects. On the machine tool level, authors focused on cutting force prediction along the tool path [Altintas 1991], [Yun 2003a]. [Lin 1996] presented the importance of the interpolator function and settings of the tool centre point movement. Simulations of the interaction between the machine tool structure and the feed drive control were presented by [Weck 2003], [Brecher 2004] and [Vesely 2009]. A comprehensive virtual machine tool model consisting of structural properties, control and thermal deformation was published by [Yun 2003b]. Coupled models of structure and feed drive control were published by [Zaeh 2004]. Erkorkmaz and Altintas proposed a method for feed drive control parameter tuning using a virtual machine tool [Erkorkmaz 2001a,b,c]. Pritschow et al [Pritschow 2004] presented hardware in the loop simulation of tool path control and methods for evaluation of feedback control stability.

There are various papers focusing on simulation of the cutting stability along the tool path and prediction of the workpiece surface quality. Methods for simulation of the machining process interaction with the machine tool structure and tool path control were presented by [Denkena 2002] and [Brecher 2005]. The state-of-the art in virtual machining is presented in [Altintas 2014]. Constructive Solid Geometry (CSG) is used for geometric representation of the workpiece and tool during surface quality simulation [Surmann 2008]. This method is used to predict the surface quality affected by machining vibration [Kersting 2009]. The dynamic properties of the thin walled workpiece can also be taken into account [Wiederkehr 2016].

As can be seen, methodology for developing a virtual machine tool is generally well known. Publications predominantly focus on the coupling of the structural model with the feed drives and the control system. Authors are typically most concerned with predicting machining stability and related surface quality. There are no published papers focused on setting the control system with respect to workpiece surface quality. This paper presents a procedure for building a virtual machine tool including verification of its dynamic properties. There is a particular focus on the influence of the control system interpolator on machining productivity and workpiece surface quality. This influence is demonstrated by the shortened machining time due to the optimal setting of the control system interpolator parameters. The results of the virtual machining and the real machining are compared. The Heidenhain iTNC530 was used for both the virtual and real cases.

This paper is structured as follows: The virtual machine tool model and the process of virtual machining are described in section 2. Virtual machining of a specific part including results comparison with real machining is presented in section 3. Optimization of the machining process using the virtual machine tool is presented in section 4. The results and the potential of the approach are discussed in section 5.

2 VIRTUAL MACHINING WITH A VIRTUAL MACHINE TOOL

The workflow of virtual machining using a virtual machine tool is presented in Fig. 1. The virtual machine tool consists of a model of the machine tool structure (represented as state-space model describing its dynamical compliance), the machine feed drives including their control and the CNC control system interpolator.

The machining process is typically planned using CAM software considering workpiece fixture position, toolpath strategies for cutting tools with various specific shapes and cutting conditions along the tool path. The aim is to perform anticollision check of the NC code. The NC code is an input for the virtual machine tool model. The contour errors along the toolpath are obtained as an output of the simulation. The virtually machined workpiece surface is visualized by material removal simulation in specialized visualisation module considering the real cutting tool envelope.

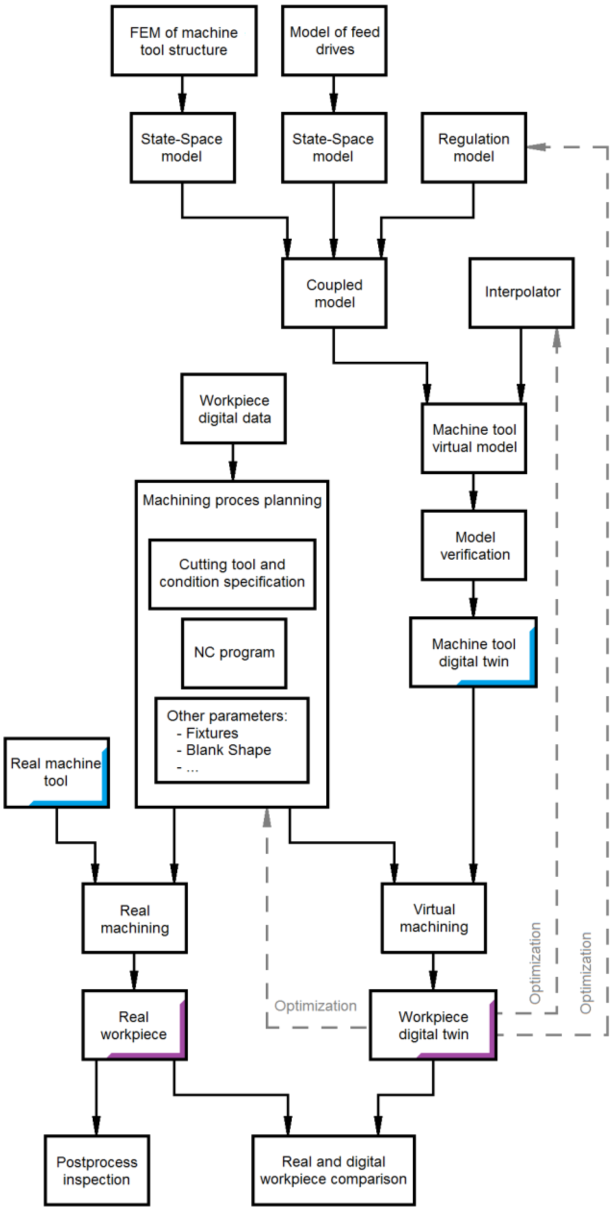

Figure 1: Workflow of virtual machining using virtual machine tool, real machining and comparison of both.

This level of the virtual machine tool does not involve cutting process simulation. Thus, only toolpath errors caused by the interpolator processing of the NC code and subsequent interaction between the feed drive and structure can be simulated. Therefore, a typical application is a finish milling operation. Various tool path errors caused by the NC code and its interpretation are most visible in free form machining particularly if ball end mills are used. The described virtual machine tool enables three types of process optimization on the virtual level for checking how the applied changes affect productivity, quality and accuracy of the workpiece:

- Optimization 1: Optimization of the feed drive control parameters. Position gain Kv, control loop bandwidths and filter setting are the most important parameters related to the mechanical structure properties. The feed drive control setting can significantly influence the process results. This optimization is not used in this paper.
- Optimization 2: Optimization of the interpolator parameters. There are many options for setting the interpolator. They are most significant with respect to the machining process: tolerance at corners for movements at machining feed rate; limit frequency for advanced HSC filter; tolerance for curvature changes with advanced HSC filter; maximum permissible axis-specific jerk at corners for advanced HSC filter; maximum permissible axis-specific jerk at curvature changes for advanced HSC filter [Heidenhain 2010]. This optimization is explained and presented in this paper.
- Optimization 3: Optimization of the NC code. Various changes influencing the NC code, e.g. machining strategy, tool path, tool revolutions and contour feed [Vavruska 2018] can be tested using the described virtual machine tool. This optimization is not used in this paper.

This paper is focused on demonstration of the Optimization 2 approach on the example of a five-axis portal milling machine with a rotary tilting head.

2.1 Intepolator simulation

The main role of the interpolator is to transform the geometry-based information in the NC code to the time-based input data for the feed drives. This transformation is done with respect to the kinematic structure of the machine tool. Various functions controlled by many parameters are used to ensure smooth machine tool movement within defined tool path tolerances [Heidenhain 2010]. Since the interpolator also has a significant impact on the productivity, accuracy and quality of finishing, the interpolator has to be part of the virtual machine tool to ensure the right input signals for the model of the structure and feed drives.

There are two possible ways to do this. As a first option, it is possible to use the interpolator of a real machine tool [Altintas 2005], [Vesely 2009]. A “true machine tool interpolator” is used in this case. Thus, the output data are identical to real machining. The other option is to use the virtual station used for NC code simulation. These stations are available from various control system producers. The station also contains the control system interpolator. An important advantage of this solution is that the simulation can be run faster than real time. On the other hand, this interpolator is not identical to the “true machine tool interpolator” and some differences in results may occur. Thus, the kinematic transformation setting and interpolation functions have to be verified when a virtual programming station is used.

A virtual programming station was used in the presented approach. In the first step, the kinematic structure of the machine tool was defined in the programming station. The kinematic transformation quality had been tested through a spherical surface machining test. The tool centre point moves over the sphere on two half-circle trajectories (see Fig. 2). The sphere diameter is 100 mm and the requested tool centre point movement speed is 1 m/min. The tool axis is oriented through the sphere centre all the time. Five-axis movement control is used. A comparison of the tool paths generated by the virtual station and by the real machine tool (position setpoint signal generated by interpolator for both cases) confirms that the setting of the kinematic transformation in the virtual station is correct. The results comparison can be seen in Fig. 3. If we neglect errors in the first and last trajectory points caused by different simulation and experimental initial positions, the errors are below 1 μm. This is a very good concordance between the simulated data and the real data gained from the real machine tool control system.

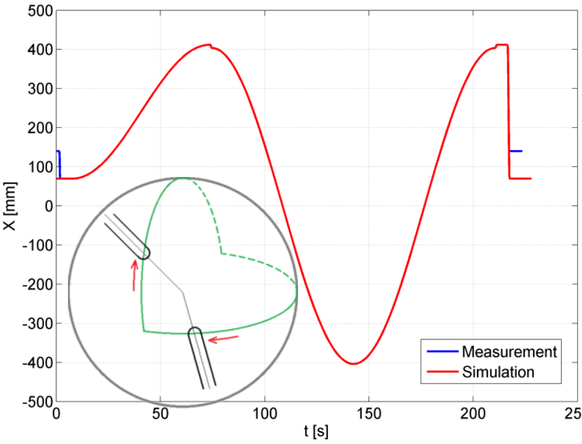

Figure 2: Interpolator verification using two half-circle tool path: example of X axis results.

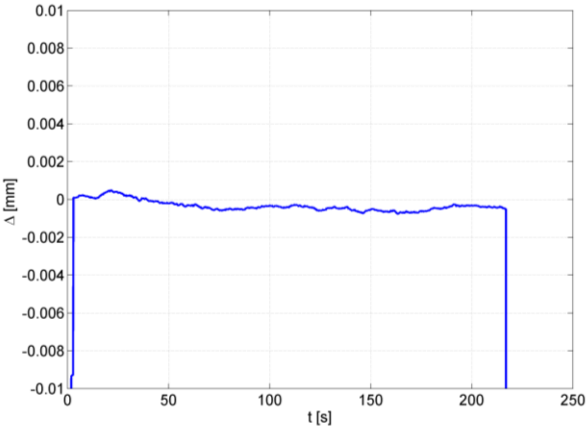

Figure 3: Position difference between tool paths generated by the virtual programming station and the real machine tool.

The interpolator function should be verified in the next step. Though the spherical surface machining test was also used, the interpolator setting validation was mainly performed on a simple testing workpiece (Fig. 11) used for three-axis machining. The maximum error along the toolpath (also position setpoint signals) was about 3 μm. The machining time prediction error was about 100 ms within the 70 s testing cycle, i.e. the time prediction error was about 0.15 %. With respect to the results of kinematic transformation verification, tool path interpolation and the machining time prediction, it can be stated that the virtual station is able to replace the real machine tool interpolator with very good concordance.

2.2 Model of structure and feed drives (coupled model)

Coupled model includes finite element (FE) representation of the machine tool structure (see Fig. 4) together with the feed drive mechanical structure and feed drive control. FE model provides an important information on the modal properties of machine tool structure, which is interacting with the feed drives and their control. If the FE model is not considered and only a simplified lumped mass representation of the machine tool motion axes is used, virtual machining simulation can not deliver relevant prediction of the tool center point vibration [Vesely 2009]. In order to achieve time efficient machining simulation, the machine tool FE model is transformed using modal decomposition technique into the state space representation (Fig. 5).

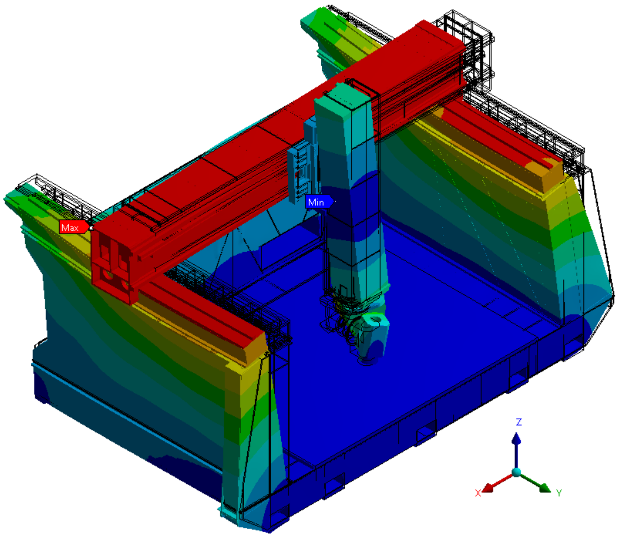

Figure 4: Fe model of the five-axis portal milling machine with a rotary tilting head used in this study and its typical first structural eigenmode.

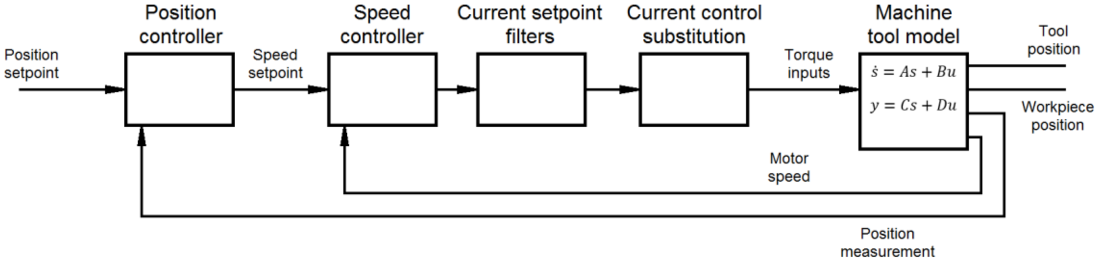

Figure 5: Simplified schema of the linear feed drive control. The structure of the machine tool and the mechanical structure of drive components are presented using the state space model.

The machine tool coupled model can efficiently be verified by velocity control loop transfer functions of each motion axis. An example of the comparison of the model results and the measured characteristics for X axis is presented in Fig. 6. As can be seen, the model match with the measured data is quite well.

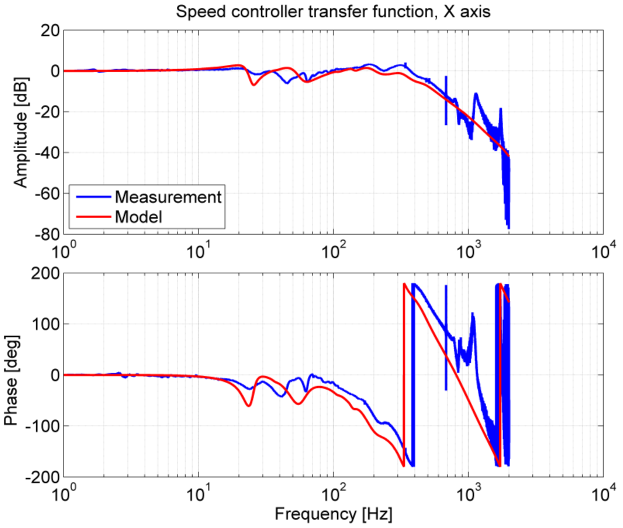

Figure 6: Example of verification of the machine tool coupled model - comparison of speed controller transfer function of X axis

2.3 Machining simulation using the virtual machine tool

The virtual machine tool consists of the interpolator and the model of the structure and feed drives. The input NC code is processed with the interpolator. As a result, the position setpoint time signals for all linear and rotational axes are obtained and used as inputs for the feed drives in the coupled model. The outputs of coupled model are the position time signals of the tool centre point (TCP) and the inclination and tilting of the tool axis and position of the workpiece. This information is computed with the time step of the interpolator i.e. usually a few milliseconds (depending on the control system type). The volume of the workpiece is split into smaller sub-volumes using the voxel technique. The information about the TCP position and its axial orientation is used to analytically describe the position and shape of the tool (typically a cylinder, ball or similar shape) in the virtual working space of the machine tool. A distance field function [Jamriska 2010] is computed for every tool position. Decisions about the cut/uncut material in voxels or shape of the machined surface within the voxel are the main results of the distance field function analysis. This analysis is not continuos nor interpolated between the interpolator time steps, so the resulting machined surface is combined from these discrete “cuts”. Thus these results is mostly unsuitable for roughness estimation even though they are fine enough for applicable visualisation; see example in the following section.

3 EXAMPLE OF VIRTUAL MACHINING

A digital twin of the five-axis milling machine with a rotary tilting head (Fig. 2) was used for the initial simulation of the machining process. The tested workpiece was an aluminium mould (Fig. 8). The requested surface quality was Ra = 1.6 μm. The requested surface profile tolerance range was ±0.1 mm. All machining operations (roughing, semifinishing and finishing) were simulated. The results of the last finishing operation are presented in the following section. This operation was the most time-consuming operation in the whole process.

3.1 Virtual machining results

The virtual machine tool model included the described interpolator (see section 2.1) and the coupled model of the machine tool (see section 2.2) was used for the simulation. The interpolator setting for this initial machining is presented in Tab. 1. The machining time predicted by the model was 7761 sec. The finished surface of the workpiece is the result of the virtual machining simulation (see Fig. 7). According to the simulation, the surface shape inaccuracies were within the requested surface profile tolerance range of ±0.1 mm. The surface errors outside of the tolerance range are marked in red. The reason for the error is that the ball end mill ∅ 2 mm that was used was not able to produce the requested surface radius due to tool holder collision. However, this is a process planning issue that is not relevant to the simulative and real machining comparison.

Table 1: Interpolator setting used for the initial machining of the mould. This setting was used on the real machine tool as well as in the digital twin of the machine tool.

Parameter	Meaning	Set value
MP1202.0	Tolerance at corners for movements at machining feed rate	0.05 mm
MP1213	Limit frequency for advanced HSC filter	10 Hz
MP1223	Tolerance for curvature changes with advanced HSC filter (0: tolerance is not included, 1: tolerance is included)	1
MP1233.x	Max. permissible axis-specific jerk at corners for advanced HSC filter	5 m/s^3
MP1243.x	Max. permissible axis-specific jerk at curvature changes for advanced HSC filter	5 m/s^3

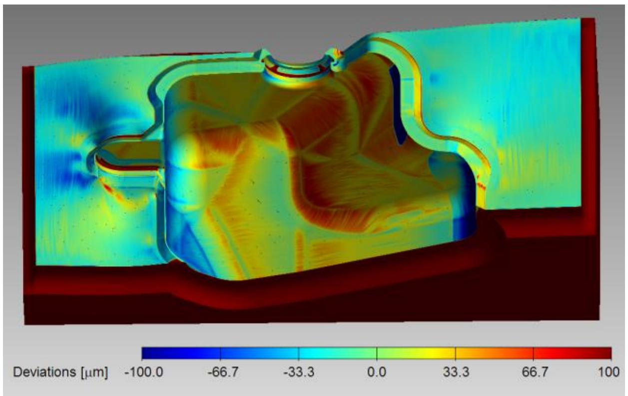

Figure 7: Visualization of the shape errors on the virtually machined surface (initial interpolator setting).

3.2 Real machining results

The simulation results were compared to the results of the real machining. The part was machined on the real machine tool (Fig. 8). The final surface shape was scanned using the SIP CMM5 coordinate measurement machine; see Fig. 9. The machine uses ruby sphere of diameter 6 mm. The scanning procedure is as follows: Firstly, position of six selected points is measured for identification of the spatial position of the part. Secondly, there is defined 50 points for measurement. The measurement machine moves to the part on surface normal vectors obtained from the CAD model. Best-fist adjustment of the real part spatial position compared to ideal CAD model is computed. Then, as a last step, position of 1148 points (a compromise between measurement accuracy and measurement time) is measured using the same procedure as in the second step. The best-fist adjustment of the real and CAD virtual model is computed again. This last fit is used for final computation of the surface errors.

The real machining results show that the majority of the surface error was within the defined surface profile tolerance of ± 0.1 mm. Only the surfaces with a low radius finished with the ball end mill ∅ 2 mm are outside of the tolerance. Thus, the machining simulation results are similar to the real machining results. Different methods were used for the virtual and real surface error evaluation (compare Fig. 7 and Fig. 9). For virtual machining, the coordinate systems of the ideal and machined surface were unified. The errors are thus absolute. In contrast, for real machining, there is no way to obtain the coordinate system of the real workpiece. Therefore the ideal shape was fitted in all 6 DOFs according to the lowest average error value. The real machining time was 7783 sec; see the results overview in Tab. 3. The surface roughness was also checked on the machined part. A value of Ra = 0.93 μm was measured, which is within the requested surface quality.

Figure 8: A view of the tested workpiece (aluminium mould). The workpiece surface after finish milling with the initial setting of the interpolator is presented.

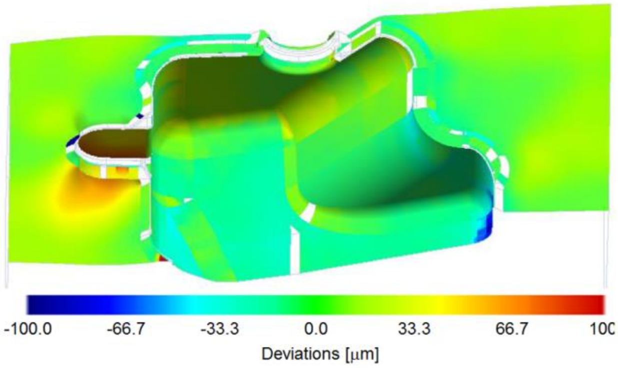

Figure 9: Scanned surface errors on the real workpiece finished with the initial interpolator setting. The presented colored areas are within the surface profile tolerance range of ± 0.1 mm.

3.3 Results comparison and discussion

The presented example shows that virtual machining using a digital twin of the machine tool is very well suited to predicting the machining time and the surface quality. The simulation model does not involve a cutting force model. Therefore, the presented digital twin is relevant for complex machining operations with minor cutting forces. The typical example of such operations is a finish milling using a ball end mill. The workpiece should be stiff. The cutting forces cannot be neglected if the structural stiffness of the tool or the workpiece are an issue that limits the machining stability and accuracy [Wiederkehr 2016].

In addition, due to the high resolution of the results, virtual machining can be used to check surface quality. Minor visual surface errors caused by various reasons within the defined surface profile tolerance can be found and improved using the simulation results. In the example in Fig 10, it is possible to see a finished surface errors (highlighted with color diference in simulated surface picture) caused by the interpolator setting.

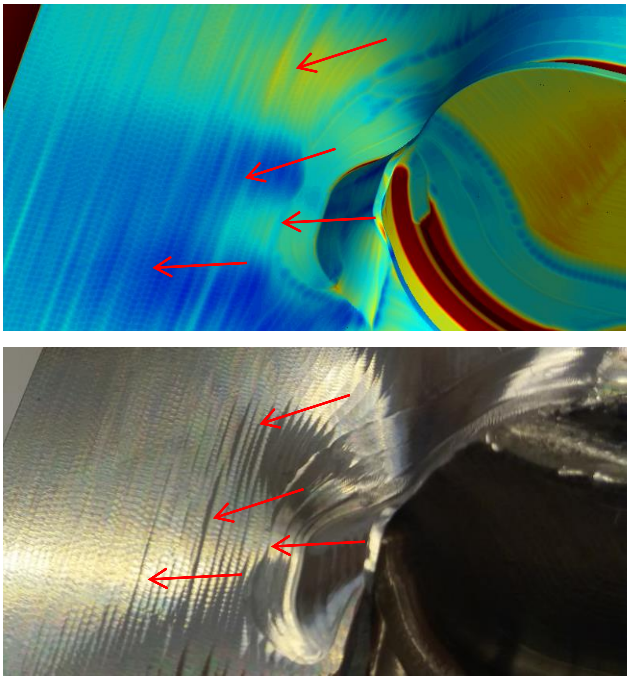

Figure 10: Examples of minor surface errors. Detail of the middle left area of the part. Picture of simulated surface above, photo of machined surface below.

4 PROCESS OPTIMIZATION USING THE VIRTUAL MACHINE TOOL

The digital twin of the machine tool can also be used for various types of process optimization in the virtual space (see overview in section 2). In this section, application of the described digital twin of the portal milling machine with a rotary tilting spindle head is used for optimization of the interpolator parameters.

4.1 Interpolator parameter optimization

The interpolator transforms the geometry-based information in the NC code to time-based input data for the feed drives. This transformation is done with respect to the kinematic structure of the machine tool. The transformation can be controlled with specific control system parameters. The most important parameters are parameters for setting the geometrical tolerances of the generated tool path (real tool path tolerance range, frequency of the tool path curvature changes, etc.) and the dynamic limits of feed drives (jerk limits). In this case, the Heidenhain iTNC530 control system was installed on the machine tool. There are five key parameters that significantly influence productivity and accuracy which were selected as the most significant for machining result control:

- MP1202.0: Tolerance at corners for movements at machining feed rate.
- MP1213: Limit frequency for advanced HSC filter.
- MP1223: Tolerance for curvature changes with advanced HSC filter.
- MP1233.x: Maximum permissible axis-specific jerk at corners for advanced HSC filter.
- MP1243.x: Maximum permissible axis-specific jerk at curvature changes for advanced HSC filter.

A test workpiece with a simple geometry consisting of linear and arc sections for three-axis milling was used for pre-testing various combinations of the interpolator parameter settings for the finishing operation (Fig. 11). The results of machining were evaluated through a visual inspection of the surface quality. Subsequently, the interpolator parameters were changed for roughing, semifinishing and finishing operations (Tab. 2).

4.2 Virtual machining results

The recommended interpolator setting that had been identified through experiments was tested on the real part using the digital twin of the machine tool. The only criterion for the roughing and semifinishing operations was shortening the machining time. The criteria for the finishing operation were surface errors and machining time. The simulated results were compared with the real machining results; see Tab 3. A detailed overview of the process before and after interpolator setting optimization is presented in Appendix 1.

The surface error prediction for the last finishing operation is presented in Fig. 12. Compared to the non-optimized initial state (Fig. 7), the darker red and blue areas show where surface accuracy is worse. However, the shape of the final part remained within the defined surface profile tolerance, i.e. the machine tool with the optimized interpolator setting uses the full tolerance range. As a subsequent result, the machining time was shortened by about 18.4 % (comparing total machining time resulting from both simulation results; see Tab 3).

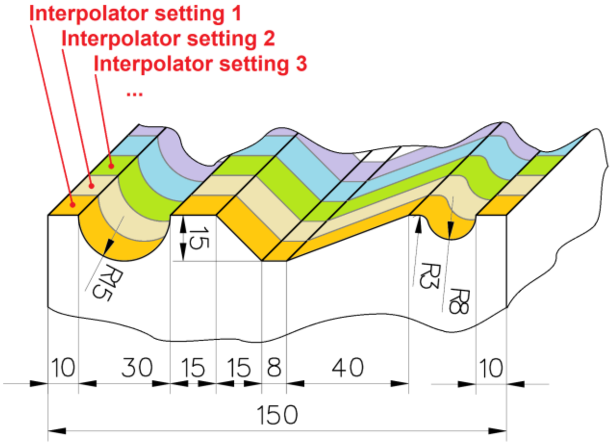

Figure 11: Scheme and dimesions of test workpiece for three-axis milling evaluation of the surface quality with respect to the various interpolator parameter settings

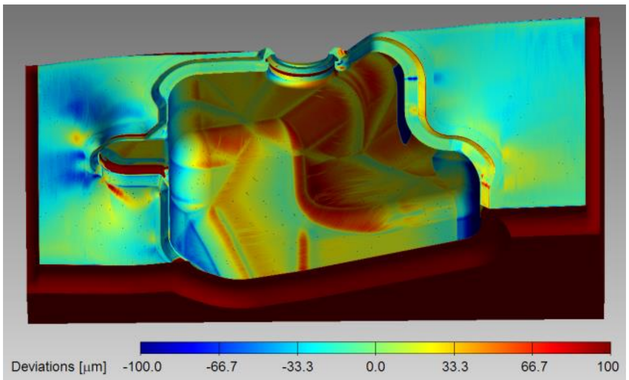

Figure 12: Visualisation of shape errors on the virtually machined surface (optimized interpolator setting).

Table 2: Interpolator setting used for the initial machining and the optimized machining of the mould. The parameters used for roughing and semifinishing operation are presented in the table.

Parameter	Initial value (used for all operations)	Optimized value (roughing)	Optimized value (semifinishing)	Optimized value (finishing)
MP1202.0	0.05 mm	0.2 mm	0.1 mm	0.05 mm
MP1213	10 Hz	10 Hz	10 Hz	10 Hz
MP1223	1	0	0	0
MP1233.x	5 m/s^3	65 m/s^3	65 m/s^3	5 m/s^3
MP1243.x	5 m/s^3	65 m/s^3	65 m/s^3	65 m/s^3

Figure 13: View of the tested workpiece after finish milling with the optimized interpolator setting.

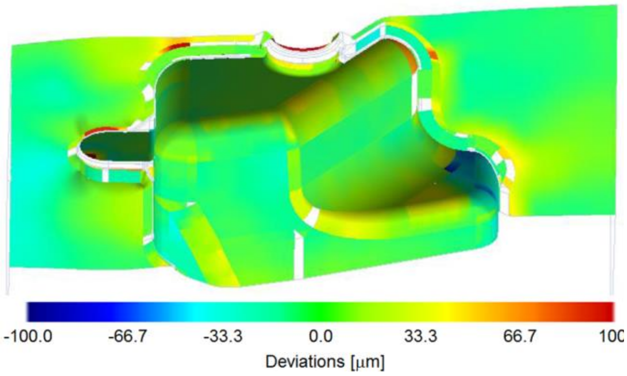

Figure 14: Scanned surface errors on the real workpiece finished with the optimized interpolator setting. The colored areas are within the surface profile tolerance range of ± 0.1 mm.

4.3 Real machining results

The optimized interpolator setting (Tab. 2) was also used in the real machine tool for machining of the mould workpiece. The surface of the final part was checked with scanning again, using the same method. As can be seen (Fig. 14), the majority of the surface area stayed within the requested surface profile tolerance. The minor out-of-tolerance areas are the same as with the finishing operation using the initial interpolator setting. These errors were not caused by machine tool control. The main reason for these errors was the tool path shape defined with the NC code, which does not change.

The surface roughness was checked on the machined part again. A value of Ra = 0.87 μm was measured. The difference compared to the machining with the initial interpolator state is within measurement uncertainties. Thus it is possible to say that the finish machining with the optimized interpolator parameters generated a similar surface roughness. Concurrently, the machining time was shortened by about 18.4% (comparing total machining time resulting from both real machining results; see Tab 3).

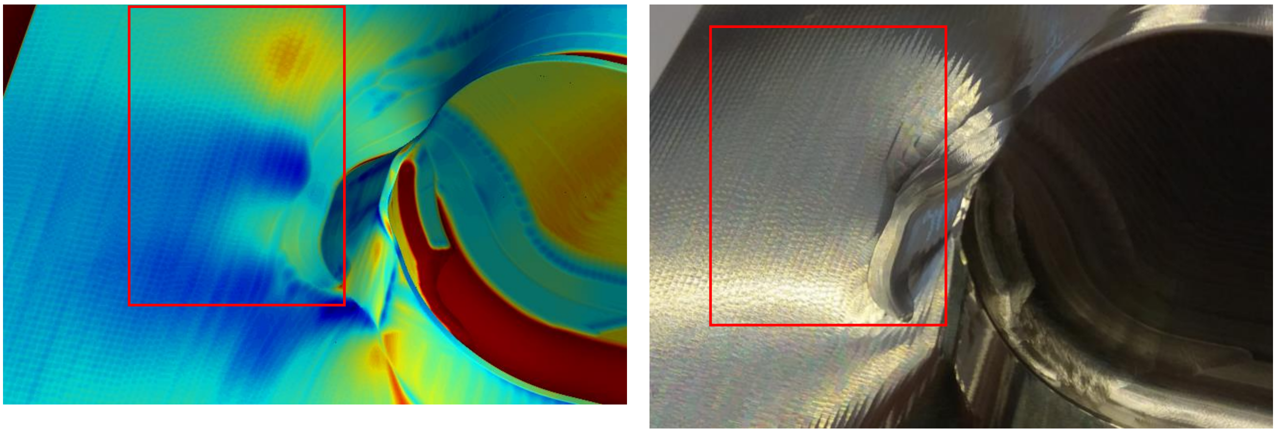

Figure 15: Examples of the machined surface structure. Detail of the middle left area of the part. Picture of simulated surface is on the left side, photo of machined surface on the right side.

4.4 Results comparison and discussion

A comparison of the simulated and real machining time shows that the virtual machine tool model provides 1:1 machining time prediction with the is error lower than 1 % for the process considered (see Tab. 3).

As shown above, the virtual machine tool model is also a useful tool for optimization of the whole process. In this case, optimization of the interpolator parameters had a significant impact on the machining time. Various settings were pretested on the specific real machine tool on the simple three-axis test workpiece. The selected parameter set was later tested using the virtual machine tool for machining of the geometry of the real part. Since the surface quality and accuracy were acceptable, the optimized interpolator setting was implemented into the real machine tool. This modification of the interpolator setting (Tab. 2) enabled machining time savings about almost 18 %. This result demonstrates that the interpolator setting can be a significant part of process optimization for shorter production time with respect to the defined workpiece accuracy and quality.

The comparison of surface structure on the virtual workpiece and the real workpiece show similar results; see Fig. 15. These final results confirmed that the proposed virtual machine tool model and virtual machining approach are useful for checking surface quality before running a real process.

Table 3: Overview of machining time results. A comparison of the virtual process simulation and real machining process is shown. Time savings due to the optimized interpolator setting are also presented.

		Virtual process simulation [sec]	Real machining process [sec]	Estimation error of the simulation
Original process	Longest finishing operation	3502	3500	0.06%
	Part production total time	**7761**	**7783**	0.28%
Optimized process	Longest finishing operation	2928	2926	0.07%
	Part production total time	**6335**	**6352**	0.27%
Machining time savings after process optimization	Longest finishing operation	16.4%	16.4%	
	Part production total time	**18.4%**	**18.4%**	

5 DISCUSSION

The presented virtual machine tool model consists of the structure of the machine tool (structural bodies, mechanical structure of the axis drives, control of the feed drives) and the interpolator of the control system. Each part of the model (the structure model and the interpolator setting) has to be verified separately before the parts are used together. The presented virtual machine tool model does not include a model of the cutting process or a model of the dynamic properties of the workpiece. A typical application of the model would be e.g. finish milling of moulds where cutting forces are relatively low and the workpiece is stiff. The typical outputs of the model are predicted machining time and surface accuracy and quality.

The machining time prediction is more accurate than the usual CAM simulation because the model includes the interpolator for computation of the time-dependent data for the machine tool feed drives. As shown in Tab. 3 and Appendix 1, the prediction error is typically lower than 1%.

The presented virtual machine tool model is also suitable for predicting surface quality and accuracy. The model can be used to analyze the surface errors caused by the dynamic behavior of the whole chain interpolator-feed drive control-mechanical structure. Workpiece surface accuracy with respect to the defined surface profile tolerance can be evaluated. The surface structure can also be checked, as presented on the examples above. The model is not able to address geometric and thermal errors of the machine tool structure or errors related to workpiece clamping.

Since the model provides very good match with the real machining results, it can be used as a tool for checking the real process chain setting. The presented use case demonstrated that the appropriate setting of the interpolator parameters can shorten the machining time significantly. As described, it is useful to use various interpolator settings for various applications. The other result is that the information about the surface quality obtained on the test workpiece is applicable to optimization of the more complex real workpiece.

In the presented cases, only the CNC interpolator parameters were changed. In general, there is additional potential for shortening machine time through appropriate tool path planning and NC code generation using a postprocessor.

6 CONCLUSION

This paper presents a virtual machine tool model and its application for machining process optimization. The model includes the machine tool structural parts, mechanical structure of drives, control of feed drives and interpolator. The model is able to compute tool centre point position and tool orientation in the defined work space. This information can be used for visualisation of surface quality and accuracy.

The model is suitable for testing various NC codes, feed drive settings and interpolator settings of the accuracy, quality and productivity of machining. The virtual machine tool model is able to predict machining time with an error of about 1%. The surface structure can also be simulated including various minor shape errors on the workpiece surface.

As was demonstrated, the interpolator setting can significantly influence the machining time and to some extent surface quality. Machininig time reduction potential is about 10 – 20 %. Optimization of the interpolator setting for every partial operation would be a recommended procedure for achieniv an increased productivity.

7 ACKNOWLEDGMENTS

The authors would like to acknowledge funding support from the Czech Ministry of Industry and Trade under the project FV10204 "Virtual machining as a support of advanced manufacturing technologies for productive and precise machining of complex-shaped parts". Support from the BLUE RAY company for experiments is also gratefully acknowledged.

8 REFERENCES

[Altintas 1991] Altintas, Y., Spence, S., Tlusty, J. End Milling Force Algorithms for CAD Systems. CIRP Annals, 1991, Vol. 40, Issue 1, pp. 31-34. ISSN 0007-8506

[Altintas 2005] Altintas, Y., Brecher, C. Weck, M. and Witt, S. Virtual Machine Tool. CIRP Annals, 2005, Vol. 54, Issue 2, pp. 115-138. ISSN 0007-8506

[Altintas 2014] Altintas, Y., Kersting, P., Biermann, D., Budak, E., Denkena, B. and Lazoglu, I. Virtual process systems for part machining operations. CIRP Annals, 2014, Vol. 63, Issue 2, pp. 585–605. ISSN 0007-8506

[Brecher 2004] Brecher, C., Witt, S. Static, Dynamic and Thermal Behaviour of Machine Tools with Regard to HPC. In: Proceedings of International CIRP Conference of High Performance Cutting (HPC), Aachen, 2004. RWTH, pp. 227-242. ISBN 3926690011

[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., Integrierte Simulation von Prozess. Werkstück und Maschine, Tagungsband 25. Aachener Werkzeugmaschinen Kolloquium, 2005, pp. 307-350.

[Denkena 2002] Denkena, B., Tracht, K., Rehling, S., Simulationsmodul für Maschinendynamik im Rahmen eines Fertigungssimulationssystems. WT Werkstattstechnik online, 2002, Vol. 92, Springer-VDI-Verlag, Düsseldorf, pp. 223-225.

[Erkorkmaz 2001a] Erkorkmaz, K., Altintas, Y. High speed CNC system design. Part I: Jerk limited trajectory generation and quintic spline interpolation. International Journal of Machine Tools and Manufacture, 2001, Vol. 41, Issue 9, pp. 1323-1345. ISSN 0890-6955

[Erkorkmaz 2001b] Erkorkmaz, K., Altintas, Y. High speed CNC system design. Part II: Modeling and identification of feed drives. International Journal of Machine Tools and Manufacture, 2001, Vol. 41, Issue 10, pp. 1487-1509. ISSN 0890-6955

[Erkorkmaz 2001c] Erkorkmaz, K., Altintas, Y. High speed CNC system design. Part III: High speed tracking and contouring control of feed drives. International Journal of Machine Tools and Manufacture, 2001, Vol. 41, Issue 11, pp. 1637-1658. ISSN 0890-6955

[Heidenhain 2010] Heidenhain. Technical Manual iTNC 530 HSCI, NC Software 606 420-04 and 606 421-04, February 2017

[Iwata 1995] Iwata, K., Onosato, M., Teramoto, K. and Osaki, S. A Modelling and Simulation Architecture for a Virtual Manufacturing System. CIRP Annals, 1995, Vol. 44, Issue 1, pp. 399-402. ISSN 0007-8506

[Jamriska 2010] Jamriska, O., Havran, V. Interactive Ray Tracing of Distance Fields. In: M. Wimmer, J. Hladuvka and M. Ilcik, ed. Proceedings of the 14th Central European Seminar on Computer Graphics, Vienna, 10-12 May, 2010. Vienna University of Technology, pp. 91-97. ISBN 978-3-9502533-2-0

[Kersting 2009] Kersting, P., Biermann, D. Simulation Concept for Predicting Workpiece Vibrations in Five-Axis Milling. Machining Science and Technology, 2009, Vol. 13, Issue 2, pp. 196–209.

[Lin 1996] Lin, R.S. and Koren, Y. Real-Time Interpolators for Multi-axis CNC Machine Tools. Manufacturing Systems, 1996, Vol. 25, pp. 145-149.

[Onosato 1993] Onosato, M. and Iwata, K. Development of a Virtual Manufacturing System by Integrating Product Models and Factory Models. CIRP Annals, 1993, Vol. 42, Issue 1, pp. 475-478. ISSN 0007-8506

[Pritschow 2004] Pritschow, G., Röck, S., Hardware in the Loop Simulation of Machine Tools. CIRP Annals, 2004, Vol. 53, Issue 1, pp. 295-298.

[Surmann 2008] Surmann, T., Biermann, D. The Effect of Tool Vibrations on the Flank Surface Created by Peripheral Milling. CIRP Annals, 2008, Vol. 57, Issue 1, pp. 375–378.

[Vavruska 2018] Vavruska, P., Zeman, P., Stejskal, M. Reducing Machining Time by Pre-Process Control of Spindle Speed and Feed-Rate in Milling Strategies. In: Procedia CIRP, 8th HPC 2018 - CIRP Conference on High Performance Cutting. Amsterdam: Elsevier B.V. 2018, pp. 578-581. ISSN 2212-8271. Available at: https://doi.org/10.1016/j.procir.2018.08.216

[Vesely 2009] Vesely, J. and Sulitka, M. Machine Tool Virtual Model. Modern Machinery Science Journal, December 2009, December issue, pp. 146 – 152.
DOI : 10.17973/MMSJ.2009_12_20090602

[Weck 2003] Weck, M., Queins, Q., Brecher, C. Coupled Simulation of Control Loop and Structural Dynamics. Annals of the German Academic Society for Production Engineering, 2003, Vol. 10, Issue 2, pp. 105–110. ISSN 0944-6524

[Wiederkehr 2016] Wiederkehr, P, Siebrecht, T. Virtual Machining: Capabilities and Challenges of Process Simulations in the Aerospace Industry. 16th Machining Innovations Conference for Aerospace Industry – MIC 2016. Procedia Manufacturing, 2016, Vol. 6, pp.80 – 87.

[Yun 2003a] Yun, W.S., Ko, J.H. and Cho, D.W. Development of a Virtual Machine Tool – Part 1: Mechanistic Cutting Force Model, Machined Surface Error Model, and Feed Rate Scheduling Model. International Journal of the KSPE, March 2003, Vol. 4, No.2, pp. 71-76.

[Yun 2003b] Yun, W.S., et al. Development of a Virtual Machine Tool – Part 2: Dynamic Cutting Force Model, Thermal Behavior Model, Feed Drive System Model, and Comprehensive Software Environment. International Journal of the KSPE, 2003, Vol. 4, No.3, pp. 42-47.

[Zaeh 2004] Zaeh, M.F., Oertli, Th., Milberg, J. Finite Element Modelling of Ball Screw Feed Drive Systems. CIRP Annals, 2004, Vol. 53, Issue 1, pp. 289-292. ISSN 0007-8506

CONTACTS:

Petr Kolar, Ph.D.
p.kolar@rcmt.cvut.cz
Matej Sulitka, Ph.D.
m.sulitka@rcmt.cvut.cz
Vojtech Matyska, Ph.D.
v.matyska@rcmt.cvut.cz
Petr Fojtu, Ph.D.
p.fojtu@rcmt.cvut.cz

Czech Technical University in Prague
Research Center of Manufactruing Technology (RCMT)
Horská 3, 128 00 Praha 2, Czech Republic
www.rcmt.cvut.cz

APPENDIX 1: OVERVIEW OF THE MACHINING OPERATION

Machining time is presented for real machining and virtual simulation with the initial and optimized interpolator settings. The interpolator settings are presented in Tab. 1 (initial setting) and Tab. 2 (optimized setting).

Operation	Tool	Cutting conditions	Initial machining (virtual)	**Initial machining (real)**	Optimized machining (virtual)	**Optimized machining (real)**	Real time savings
Roughing #1	Face mill 63 mm ISCAR 3 inserts 0.5 mm corner	fz = 0.25 mm ap = 3 mm vc = 2800 m/min n = 14147 rpm stepover 40 mm	499 sec	**501 sec**	390 sec	**393 sec**	22%
Roughing #2	Face mill 25 mm ISCAR 3 inserts 0.5 mm corner	fz = 0.26 mm ap = 2.5 mm vc = 1257 m/min n = 16000 rpm stepover 12.5 mm	649 sec	**653 sec**	364 sec	**367 sec**	44%
Semi-finishing	Ball mill 20 mm SANDVIK 4 flute	fz = 0,23 mm ap = 1.5 mm vc = 1131 m/min n = 18000 rpm stepover 2 mm	736 sec	**738 sec**	523 sec	**526 sec**	29%
Contouring	Ball mill 20 mm SANDVIK 4 flute	fz = 0.17 mm ap = 0.2 mm vc = 1131 m/min n = 18000 rpm stepover 0.3 mm	227 sec	**233 sec**	218 sec	**219 sec**	6%
Finishing #1	Ball mill 20 mm SANDVIK 4 flute	fz = 0.17 mm ap = 0.2 mm vc = 1131 m/min n = 18000 rpm stepover 0.3 mm	3502 sec	**3500 sec**	2928 sec	**2926 sec**	16%
Finishing #2	Ball mill 12 mm SANDVIK 4 teeth	fz = 0.1 mm ap = 0.25 mm vc = 678 m/min n = 18000 rpm stepover 0.25 mm	553 sec	**556 sec**	468 sec	**470 sec**	15%
Finishing #3	Ball mill 6 mm SANDVIK 2 teeth	fz = 0.06 mm ap = 0.15 mm vc = 339 m/min n = 18000 rpm stepover 0.15 mm	561 sec	**565 sec**	493 sec	**497 sec**	12%
Finishing #4	Ball mill 2 mm SANDVIK 4 teeth	fz = 0.04 mm ap = 0.08 mm vc = 113 m/min n = 18000 rpm stepover 0.08 mm	1034 sec	**1037 sec**	951 sec	**954 sec**	8%
Total			7761 sec	**7783 sec**	6335 sec	**6352 sec**	**18%**