

Chapter 12

Cyber-Physical System to Improve Machining Process Performance



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12.1 Introduction

There are several tools to optimize machining processes in the design stage [1–3]. After the correct set-up of the designed process, it is run in the machine tool by an operator in production conditions.

Under ideal conditions, the operator should only run the process every time a new part is clamped in the fixture. However, different events can take the process from these ideal conditions: Tool wear or breakage, machine tool condition variation, excess/absence of material in raw surfaces, variation of workpiece material, variation in cooling conditions, etc.

In addition, there is always some margin to improve the performance of a designed process once it is in production, for example, feed rate increase to increase productivity or feed rate reduction when process does not go as expected (e.g. chatter occurs)

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© The Author(s) 2019
M. Armendia et al. (eds.), *Twin-Control*,
https://doi.org/10.1007/978-3-030-02203-7_12

Twin-Control aims to overcome these effects by the application of CPSs based on model-based control techniques. CPSs are defined as smart devices that interact with the machine (through sensors and actuators) to increase its performance [4]. In this case, different developments of Twin-Control project in modelling are embedded in the monitoring hardware or the control of the machines to affect its performance.

After this introduction, Chaps. 2–7 present the different CPS-based control strategies in Twin-Control. Finally, the conclusions are presented.

12.2 Process Monitoring

Process monitoring using ARTIS hardware can be split into two different applications. First, process monitoring by learning. Second, process monitoring by simulation.

Learning-based process monitoring is a key feature of ARTIS process monitoring systems. The process monitoring is based on process signals of the machine control. Furthermore, the process monitoring could be based on additional sensor signals (e.g. vibration and force). Genior Modular is the main module of ARTIS hardware. In this module, the interface to the machine control as well as the HMI is provided. The process monitoring algorithm and the determination of the limits and parameters are calculated on the Genior Modular device, as well. For the user, the QNX-based Genior Modular provides an intuitive HMI to configure the process monitoring task. The system determines all limits and parameters automatically. Additional input keys provide the possibility of making certain adjustments. In detail view display mode, these input keys are immediately visible. In multi-view display mode, it is necessary to first select one of the windows in order to make the keys visible. The user has the possibility to manually adjust the limit, being less or more sensitive to process changes.

For the learning process, some reference processes must be executed in advance. The system calculates automatically how many learn steps must be performed. Apart from that, a manual adjustment of the learning process repetitions is possible.

Once the learning is complete, the process monitoring can be started. Figure 12.1 shows a visualization software GEM-Visu. Next, the most important indicators of this visualization are listed.

- Line graphics:
 - Green curve: learned signal curve
 - Grey curve: signal curves of the last 10 processes are displayed
 - Blue curve: current signal curve
 - Red curve (1): lower breakage limit
 - Red curve (2): upper breakage limit
- Bar graphics:
 - Red line (3): missing limit (indicates that a tool is not installed)

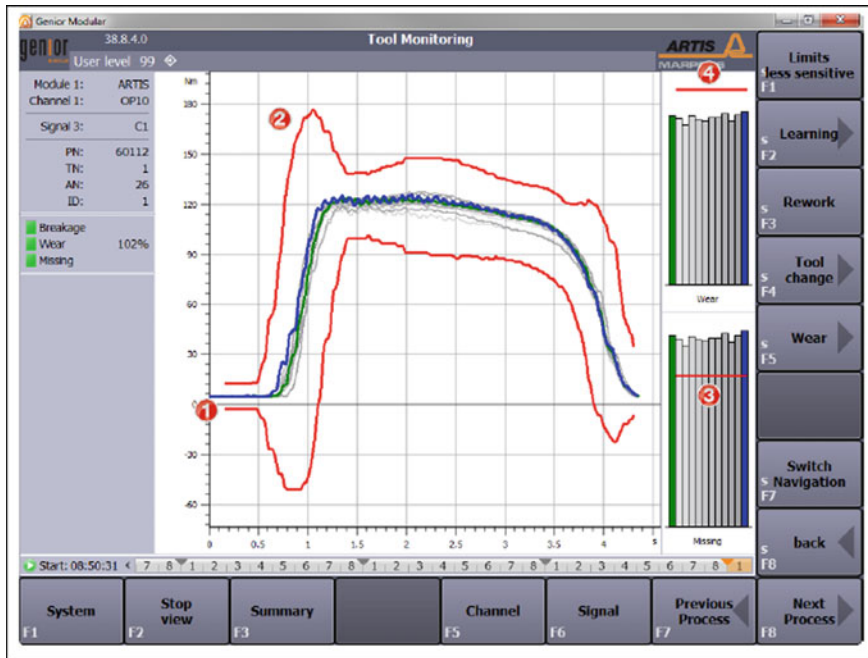


Fig. 12.1 Genior modular visualization for process monitoring

- Red line (4): wear limit
- Green bar: area value of the learned process
- Grey bar: area value of the previous ten processes
- Blue bar: area value of the current process.

The alarm reaction could be configured by the user. So, the system could send just a warning or fully stop the machine.

Process monitoring by learning is suitable for large batch manufacturing, where stable conditions are present for the learning stage and the process monitoring strategy can be applied for a long time. However, for small to medium batch size sectors, like aerospace, this approach is not useful.

For this case, Twin-Control proposes a simulation-based process monitoring. As a first step, process models are run in a PC which is connected, via CAP-Logger, to the control of the Starrag EcoSpeed located in the AMRC installations. The CAP-Logger is a small client program that connects to the GEM-CNC server via TCP and stores the requested data in CSV format. The GEM-CNC server is a service running on Siemens Solution Line HMIs. It forwards the TCP requests to the Siemens CAP-API, and it sends the response back to the CAP-Logger via TCP.

Measured axis positions and spindle speed are used as input of the models which provide spindle torque estimations. These estimations can be compared to spindle torque measurements that are also done by the ARTIS equipment (Fig. 12.2).

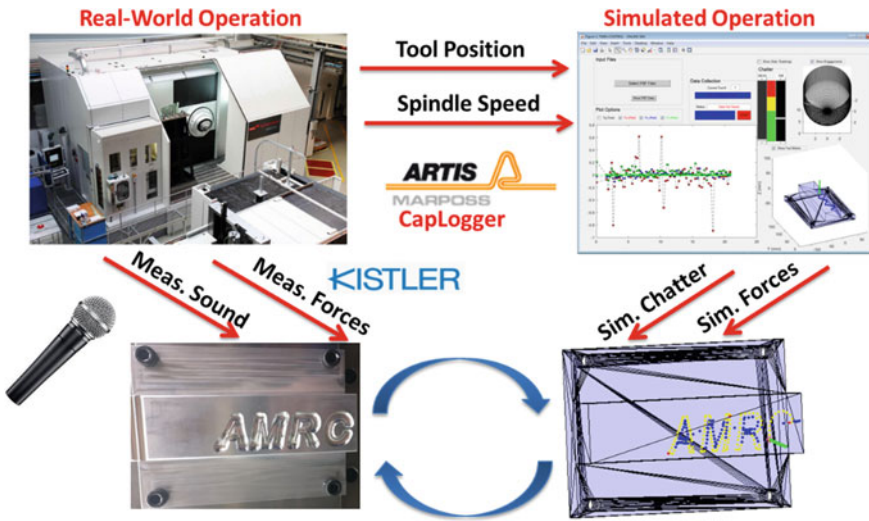


Fig. 12.2 System architecture of the pilot line set-up at the AMRC, showing the flow of data between the real and simulated operations

This strategy could be used to implement a simulation-based process monitoring. For that, process models need to be integrated into the ARTIS hardware and run in parallel to the real process (Fig. 12.3). Simulation results will provide the nominal conditions instantaneously, equivalent to the learned reference values used in the learning-based process monitoring, and could be used to fix the thresholds for a simulation-based process monitoring approach.

12.3 MT Operating Condition Adaptation for Life Increase

The knowledge of machine tool condition is very useful for maintenance activity planning. Early detection of (possible) problems in the machine tool allows more efficient maintenance actions, maximizing machine uptime.

Early detection of future anomalous situations with the machine tool avoids undesirable machine tool breakage, and consequent unforeseen production stops.

Two approaches, both based on feedback generated by models implemented by TEKNIKER in KASEM, are defined towards this end. Both models, although using different approaches, can identify or estimate that the machine tool is going to have a problem. Thanks to this feedback, ARTIS hardware can adapt, normally smooth, working conditions of the machine tool to extend machine tool life and wait for the next planned maintenance action.

The first approach is the integration of end-of-life models developed in Twin-Control project in the monitoring architecture. This feature provides the chance to

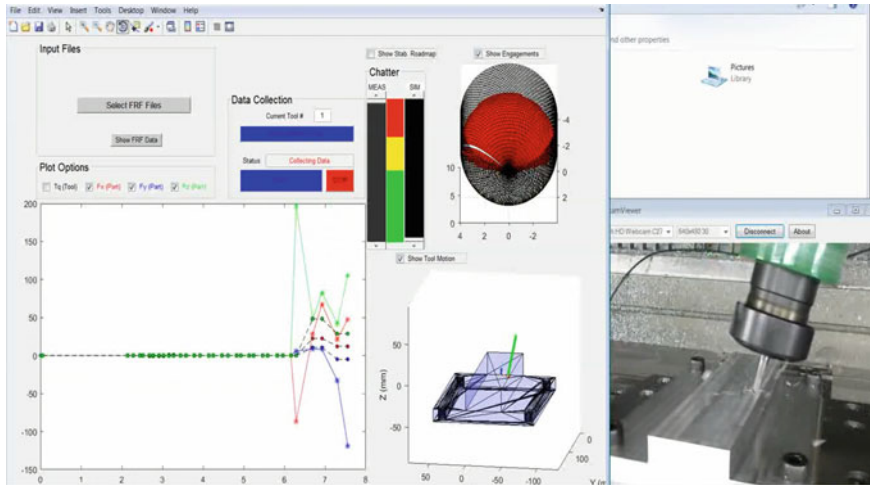


Fig. 12.3 Screenshot showing the Twin-Control process models GUI, fed with real input data coming from the machine. The estimations are directly compared with measurements of the real process, presented in lower right corner

estimate the remaining useful life (RUL) of the critical components of a machine tool by accounting for the real usage (monitored) conditions. The end-of-life models could be integrated at local or fleet level. For Twin-Control, KASEM has been the choice for this implementation. When the RUL estimated by the end-of-life model falls below a predefined limit, KASEM generates a warning towards the planning of a maintenance action (change of bearing or spindle).

A second approach is based on the results coming from the machine tool characterization tests that consist in a series of quick tests that allow a good characterization of machine tool condition. The indicators calculated from these tests are compared to the ones obtained in nominal conditions and, in case deviations occur, anomalous condition of the machine is determined. Again, even if this procedure can be implemented at local or cloud level, KASEM has been chosen as platform in Twin-Control project.

As in the case of a problematic RUL value, when any indicator of the MT characterization test gets over the defined threshold, KASEM generates a warning towards the planning of a maintenance action.

Apart from this warning at maintenance management level, Twin-Control can automatically adapt machine tool performance to its condition. According to the next planned maintenance stop and the RUL value, ARTIS Genior device system can smoothen machining conditions (reduce feed rate and/or spindle speed) to avoid component breakage. The ARTIS GEM-CNC server, installed in the machine control, receives the commands from the ARTIS GEM-OA (Genior Modular with Open Architecture) to change the current value of R-parameters that define cutting conditions (feed rate and/or spindle speed).

As an alternative to the automatic modification of machining conditions, since manufacturers do not want to decrease productivity automatically, a warning showed by the ARTIS HMI or the ARTIS telegram remote control will suggest the operator with some new cutting conditions.

12.4 Energy Monitoring System on Component Level

A cost-effective approach to monitor the energy consumption at component level has been developed by using a Kalman filter and the information of the component’s switching states, which has been explained in greater detail in Sect. 3.3.

The ARTIS OPR device records the required switching states of the different components (via OPC UA) and the power consumption of the drive (via internal signal monitoring). Additionally, the total power consumption of the machine is acquired by an ARTIS true power module. The energy disaggregation algorithm, which is based on the Kalman filter, is embedded in the ARTIS OPR.

An EMAG VLC100Y turning machine, located at the ETA Research Factory of the Technische Universität Darmstadt, has been used to implement and validate this development. The disaggregated power consumption at component level can be visualized locally on the HMI of the machine using ARTIS GEM-Visu (Fig. 12.4) or transferred to a higher-level platform, like SCADA or MES. This ensures immediate feedback on energy demand.

Even if an exact power disaggregation of industrial components is difficult, the algorithm offers a cost-effective and simple possibility to estimate the energy demand on component level. Since existing data acquisition and analysis architecture was

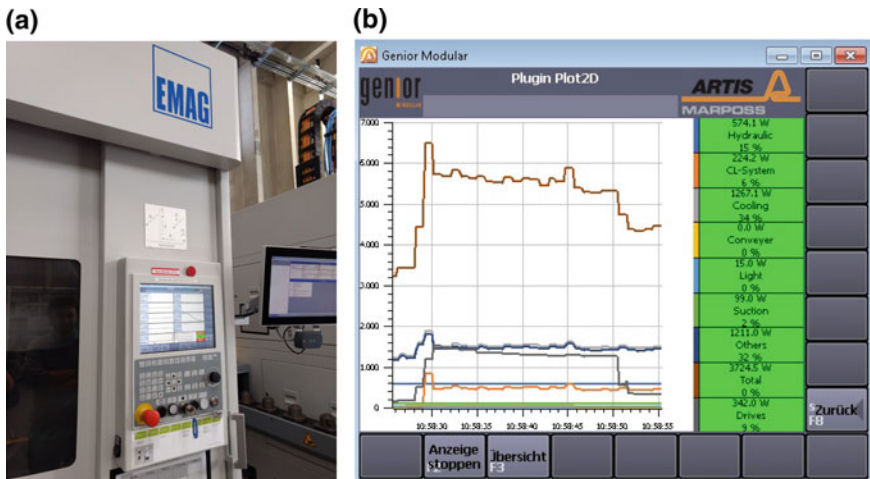


Fig. 12.4 Visualization of the component energy monitoring: a machine HMI; b ARTIS GEM-Visu

used, the implementation effort and costs could be reduced, compared to hardware-based energy monitoring on component level. The presented approach can thus be used for cost-effective energy monitoring.

12.5 Telegram Remote Control

Currently, there is no possibility to interact with the monitoring hardware from outside, so that a physical connection to the machine is needed. By using an open-source chat software for the GEM devices, a PC or a smart device could be connected to these devices from everywhere in the world.

With this approach, it is possible to get information about the status of each connected device (e.g. serial number, number of alerts, IP address) without a physical connection to it. Furthermore, it is also possible to interact with the GEM device (Fig. 12.5). Based on the configuration of the telegram adapter, monitoring configurations could be adapted via smart devices or PCs.

The telegram adapter could be installed in the GEM device or the OPR. Also, it is possible to install the telegram adapter at a plant server or PC, which has a network connection to the monitoring hardware. For connecting the monitoring hardware with a chat group, in the telegram adapter, just the IP address of the target GEM device must be configured.

For Twin-Control, a chat group was implemented, in which the GEM devices of the ARTIS, MASA and TEKNIKER use cases are involved.

12.6 Adaptive Feed Rate Control

In complex machining processes, chip flow varies according to the deep of cut, tool geometry and the programmed spindle speed. To guarantee maximum productivity, it is interesting to keep continuous chip flow control. To do that, feed rate must be adapted according to monitored spindle consumption to achieve desired variables.

Adaptive control (AC) is an option for ARTIS Genior Modular systems. This option controls the programmed feed rate of a cutting cycle to maintain a constant load on the tool during the entire cutting cycle (Fig. 12.6). This way, feed rate will be increased when the cutting power, e.g. spindle acceleration, is low (good tool condition and less chip removal). The software algorithms automatically slow down feed force if tool condition (wear) or material quality (e.g. texture, hardness) changes. This function is active during the process monitoring. To provide this feature, ARTIS Genior Modular uses the real-time connection to the machine control. By overwriting, e.g. R-parameters in the machine control, the feed rate of a cutting cycle is optimized.

Adaptive feed rate control has been implemented in the GEPRO 502 machine of MASA. This way, when the spindle is underworking, the feed rate is increased; when the spindle is overworking, the feed rate is reduced. The objective is to maximize

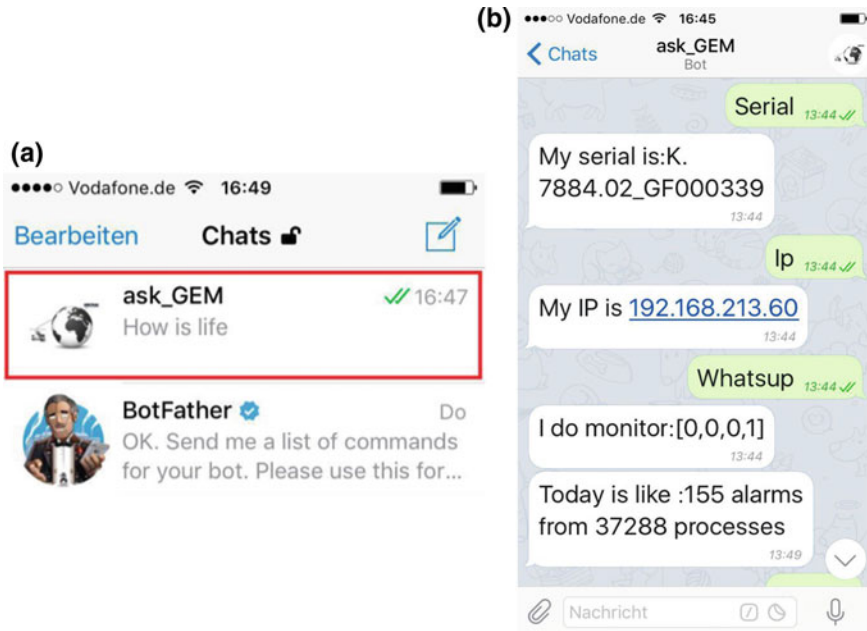


Fig. 12.5 Screenshots of the telegram adapter feature: **a** ask_gem chat within telegram app; **b** example of the contents of the chat

productivity by keeping the material removal rate high during all the process. To test this, a scalloped sample part has been used.

12.7 CNC Simulation and Collision Avoidance System (CAS)

During real machining operations, process visibility is often limited due to small safety windows or high coolant flow. Apart from that, due to undefined position of additional equipment (fixture, toolholder, workpiece, etc.) in the machine tool working volume, collisions are common. Both issues are very critical from the operator's point of view. To overcome these problems, the availability of a virtual representation of the machine tool, replicating the movements that the real machine is executing, can be very useful.

Material removal simulation is performed within ModuleWorks libraries, for which the proper simulation environment must be established first. The simulation models require the following parameters: the initial geometry of the stock material, geometric definition of the cutting tools, machine tool kinematics and a sequence of the commanded machine axis moves. Once the virtual machining set-up being initial-

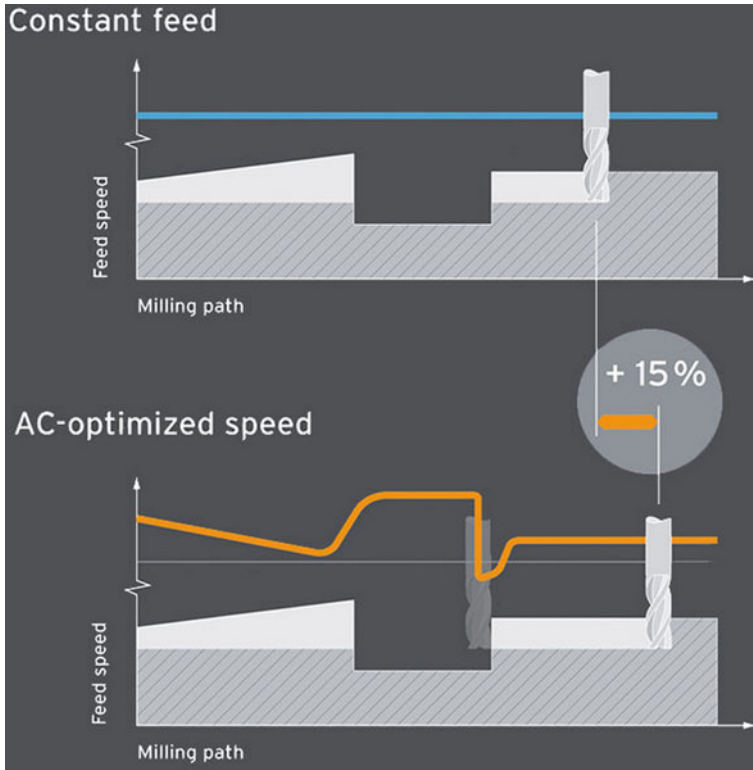


Fig. 12.6 Diagram presenting ARTIS adaptive control optimized feed rate strategy

ized, ModuleWorks simulation can retrieve input signals to change and add cutting tools, execute new cutting tool moves. During the simulation steps, the internal data structure representing the shape of in-process stock material has been continuously updating to reflect the changes made by cutting tools. For each simulated move, the output is a set of results showing the status of the tool–workpiece interaction during the move (whether material has been cut, a collision between machine tool element or cutting tool and stock material has been detected, etc.) Optionally, a tessellated (triangulated) 3D surface of the simulated workpiece can be computed for further visualization and analysis. The analysis is supported due to applying of different colorization options (coloured by tool indices, feed or another measured data). The simulation libraries are designed to be integrated on the level of the HMI or CNC unit (as shown in Fig. 12.7) to retrieve actual positions of the machine tool axes for exact computation of the relative positions of the tools and workpiece in the simulation environment. Such an approach reduces integration efforts to visualize the results and provides both verification and clash detection during different processes maintain time responsiveness.

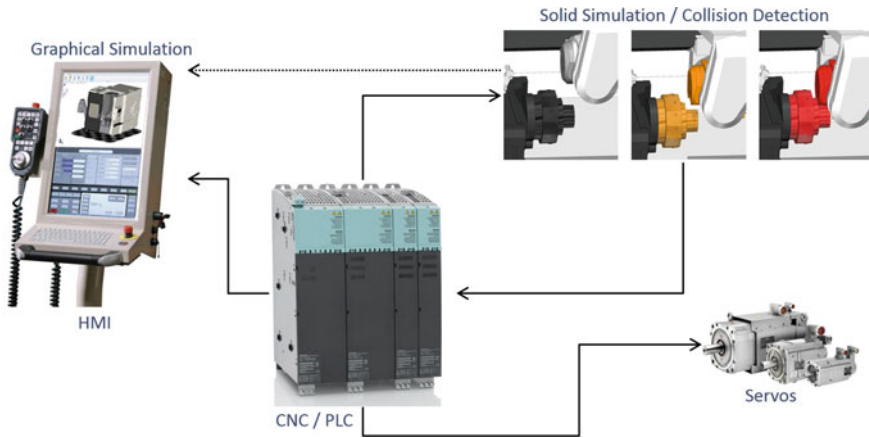


Fig. 12.7 Integration of ModuleWorks simulation

Since ModuleWorks libraries use the tri-dexel model for material shape representation, that is capable of staying memory and time consistent over machining time, this approach leads to efficient computation with a low response time that satisfies real-time conditions for machining applications.

ModuleWorks CAS takes the real axis positions, machine geometries and work-piece position and uses the same motion data as the real servos to provide a fully integrated and visually realistic simulation of the machine kinematics, tools, jaws, clamps and fixtures as well as the material removal process. The real-time collision avoidance is based on the look-ahead functionality provided by CNCs. The look-ahead is a method for trajectory planning, for which a CNC precomputes several future moves. If ModuleWorks simulation runs on the “future” moves, a message of a reported collision may be passed to the machine control before the actual collision occurs. The communication can basically be maintained through a variety of standard APIs and protocols (Focas, EtherCAT, Profinet, etc.). Collision detection and avoidance are available in both auto and jog modes using this look-ahead motion data. CAS implementation is based on the access to OPC/UA interface of the machine tool to retrieve different data via the interface along with internal processing of the geometries of the in-process stock and set-up components, as shown in Fig. 12.8.

The new functionality foresees collisions that may happen in the future. In addition to in-time simulation, simultaneous computation threads consider machine tool positions at some time upfront. The predicted position is examined towards potential collisions and may signal to halt the machine, and colliding machine tool elements are highlighted in red in Fig. 12.9.

CAS integration has been proved to be an efficient solution to withstand collision risk with different operational modes in machining critical components. Huron, a leading French manufacturer of very high-performance 5-axis machining centres for continuous machining of complex parts, has integrated CAS into Huron’s

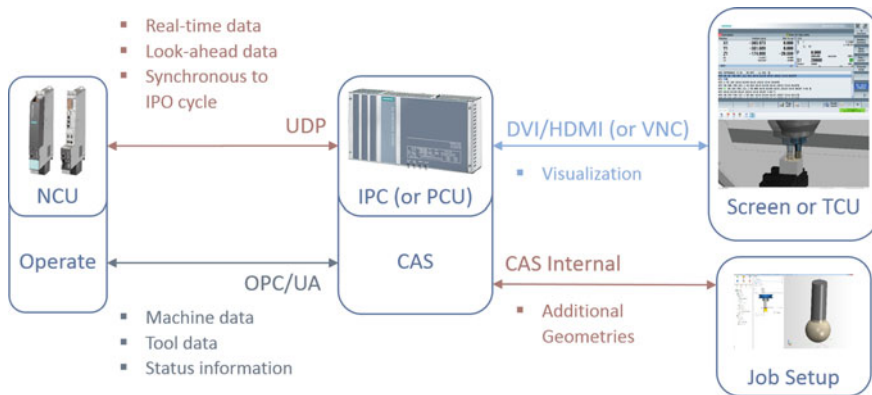


Fig. 12.8 Design of the collision avoidance system for Siemens 840D CNC

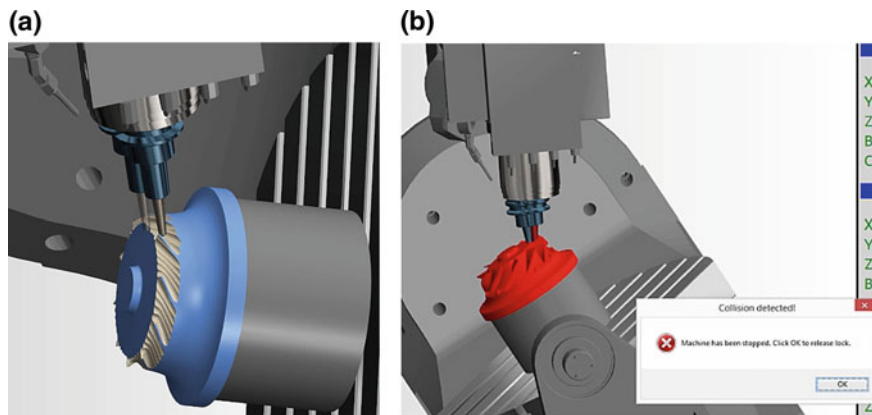


Fig. 12.9 ModuleWorks CAS in action: a look-ahead position (transparent); b CAS alarm on HMI to stop the machine

high-performance product lines, including KX 50 L, a high-performance double column machining centre, and K3X 8 FIVE, a machine from the range of very high-performance 5-axis bridge-type machining centres.

12.8 Conclusions

This document presents an overview of the model-based control strategies developed in Twin-Control project and applied using the CPS approach. Part of the modelling activities carried out in Twin-Control project has been implemented at workshop level. This way, virtual representation of the machine is linked to the real

representation and can modify its performance to improve productivity (adaptive control), increase machine uptime (collision avoidance system), optimize tool life (process monitoring), improve maintenance actions (automatic machining condition smoothening) and even to improve the communication with operators (telegram adapter). Most of the applications are based on a standard monitoring equipment, like ARTIS devices used in Twin-Control project, and hence, high costs are avoided. The different features have been validated at both laboratory and industrial level.

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