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*machine tool, intelligence,*
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# DISCUSSION OF MACHINE TOOL INTELLIGENCE, BASED ON SELECTED CONCEPTS AND RESEARCH

This paper discusses the need to create intelligent machine tools, the expected properties of such machine tools and the benefits they will bring to business and the development of manufacturing. The basis for machine tool intelligence, and the evolution of machine tools towards the development of their intelligent functions, with a special emphasis on control, digitization and virtualization systems, the role of the STP-NC standard, and the prediction of machine tool operating properties, are presented. The arising concepts of the development of intelligent machine tool functions, which take into account the monitoring and planning of a collisionless tool path, are discussed. The approach to achieving real time and the intelligent machine tool is described for copy milling. Also the directions of implementing intelligent functions by machine tool manufacturers are presented using the MAZAK Corporation as an example.

## 1. INTRODUCTION

Starting a discussion on intelligent machine tools we present first the current state of their development and the requirements they are expected to meet.

The current development of metal cutting machine tools is mainly determined by business considerations and aims at achieving the highest machining efficiency at the lowest possible costs of production and operation. Currently high efficiency is achieved through the high dynamics of the movements along the controllable axes, multitasking, the easy setup of the machine tool for machining tasks, high machine tool and machining processes precision, the reduction of idle times, efficient and friendly service and the low energy and cost intensiveness of the machine tool and the machining process. Many of the requirements are very difficult to satisfy and necessitate the prevention of various disturbances to the operation of the machine tool and the process of machining, and the very efficient control of the machine tool and the process [7],[16]. In the future the machine tool is to be capable of self-repairing while the machining process is to self-improve and holistically optimize, supervise and control itself. This necessitates an ever greater autonomy of the machine tool so that the latter is able to precisely identify disturbances in real time, using inference and

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analysis proper to a highly educated operator. The machine tool should make its own decisions as to the extent of a repair and the way of carrying it out. It is expected to allow (consistently with its autonomy) to effectively increase its precision, to eliminate on its own collisions and failure states and to optimize energy consumption. It should allow the continuous evaluation of its status and the status of the processes being carried out and should integrate a high IT level and intelligence within itself. Consequently, the machine tool will be intelligent and based on digital models, virtualization and very efficient control in real time [24].

The development of such intelligent machine tools must be based to a large extent on their great and increasingly greater autonomy and very high degree of organization. This requires increasingly higher efficiency and greater ability to cope with disturbances and counteract their consequences in accordance with a manufacturing development strategy and an adaptive machine tool control optimization strategy. The technological flexibility of machine tools, expressed in greater adaptability to tasks, must increase. Also the multitasking capability and hybridity of machine tools and their reconfigurability must keep increasing. It is assumed that machine tools will be increasingly based on knowledge and the virtualization of the design of their structure and the manufacturing process, combined with their status (including machining process variation) in real time. Designing will be based on holistic models taking into account the natural interdependences between machine tool static, thermal and dynamic properties appropriate for the operating conditions (the carrying out of machining processes). The machine tool system communication with the environment will be of increasingly greater importance for accurate control and it will be based on the latest achievements in communication and data processing standards consistently with the required active control of the operating properties in real time and with CAD, CAM and CNC requirements. The integration of monitoring and control will be increasingly better. The effectiveness of the prediction of disturbances and errors, being the basis for their active minimization and compensation, will greatly increase. Also the ability to optimize processes in real time will increase, which will contribute to the more effective self-control and self-healing of the machine tool and the machining process. The effectiveness of the integrated compensation of errors in real time, incorporated into the design and realization of the tool path in real time, will increase. Machine tools will be characterized by minimal setup times and possibly maximum productivity, which will translate into a minimal cost of manufacturing products.

Numerous studies conducted in the past and in the last decade were aimed at generating intelligent functions. The studies covered the diagnosis and supervision of the operating properties of machine tools and the machining processes, the active influencing of the properties and the compensation of errors. This paper presents the most important achievements in the development of intelligent machine tool concepts and functions.

## 2. EVOLUTION OF NC MACHINE TOOLS TOWARDS THEIR INTELLIGENCE

The foundation for the creation and development of intelligent machine tool functions was the development and implementation of the numerical controller (NC) by MIT

(Massachusetts Institute of Technology, USA) in 1952, followed by the APT machine tool programming software. Programming was done using special devices called programmators. In 1960 the advances made in control led to the creation of a direct numerical control (DNC) system storing programs which could be then directly transmitted to NCs. The first machining centre – a major step towards machine tool autonomy – was developed and implemented by the American company Kearney and Trecker in 1968. The first system integrating NC functions and computer numerical control (CNC) functions, which formed the basis for the digitization of machining process, was created in 1970. Owing to this a computer aided manufacturing (CAM) system based on computer graphics (made possible by the PC processor) was developed. The operating system was UNIX. The first modular open structure of the control system based on Windows was created in 1990, whereby it became possible to intervene in the machining process and in the operation of the machine tool in order to correct the latter's operating properties. Control systems of this class enabled integration with the latest achievements in IT and the implementation of intelligent machine tool functions through the introduction of appropriate procedures. This necessitated the assurance of the supply of necessary information to CAD, CAM and CNC modules and the machine tool and the flow of data between the modules in order to shape commands for the controllable axes (tool and positioning paths).

Numerous artificial intelligence concepts dedicated to machine tools and whole manufacturing systems have been created. They are based on intelligence patterns occurring in nature (in biology). Hence there are concepts of bionic, fractal and holonic systems [27], neural, agent and mixed systems [26] and other.

The evolution of machine tools towards the application of intelligent functions (Fig. 1) was clearly and concisely presented by [22] who distinguished three groups of breakthroughs in this evolution, consisting in the introduction of analogue control and then numerical control and finally, in the creation of an intelligent machine tool.

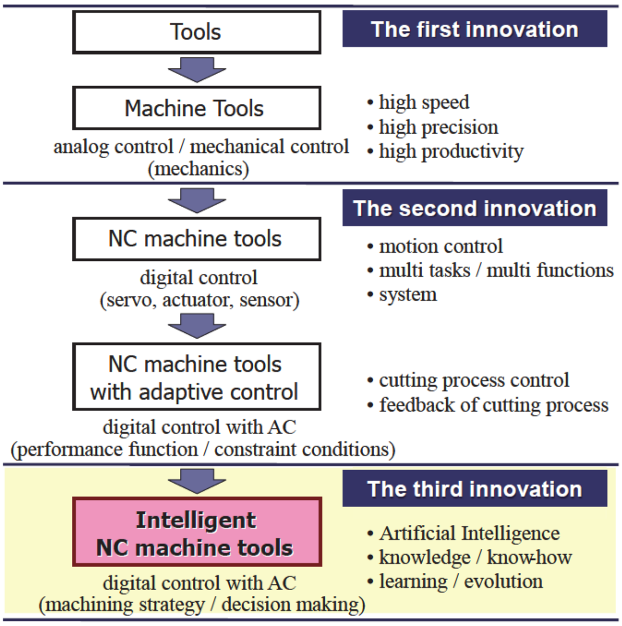


Fig. 1. Evolution of machine tools toward intelligent machine tools [22]

He noted that it was digital control which opened the way for the application of intelligent functions.

The greatest need for the application of intelligent functions is in the areas of: the reduction of errors, the prevention of chatter and failure states, the optimization of the machining process and the minimization of machining time, consumed energy, errors and costs. The multidirectional development of the application of CNC systems and open control structures, aimed at making the machining process more efficient, was analyzed with regard to openness and control streamlining by Mekid [12] and with regard to the rapid prototyping of machining processes by Ramesh [17]. Ramesh indicated the possibility of rapid CAM and the resulting great benefits.

Mekid highlighted the development leading to machine tool reconfigurability as the most advanced form of machine tool technological flexibility. He indicated the open control system’s features enabling reconfigurability, but also limitations in achieving real time at a time barrier below 1 ms cycle times (Fanuc and Siemens controllers). The currently achieved processing times are too long for the real time needs. The concept of such control is shown in Fig. 2. Its key component is the application of field programmable gate arrays (FPGA), enabling the efficient configuration of CNC and PLC controllers as one integrated circuit (a chip), which can operate parallel in real time, using a high-level language (C++, an assembler and freely programmable CPUs), signals received from sensors and real-time diagnosis.

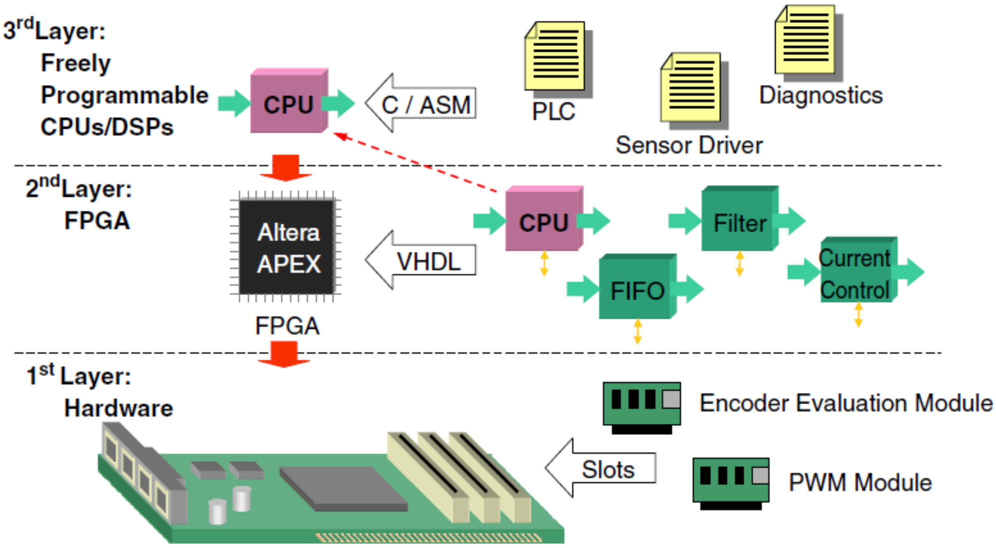


Fig. 2. Concept of open control architecture [12]

Mekid’s deliberations induced the present authors to more broadly examine the evolution of machine tool flexibility from the point of view of its effect on cost efficiency and process precision and efficiency (Table 1). It is clearly apparent that the implementation of flexibility oriented towards intelligent reconfigurability is valid and brings great benefits in every case. The gaining of great benefits from high flexibility is a function of intelligent and highly efficient control in real time. For this reason many studies have focused on this control.

Table 1. Manufacturing automation and flexibility development – proposed definition

| Flexibility | Cost efficiency | Process precision | Process efficiency |
|---|---|---|---|
| • Automation development<br>• Object orientedFlexibility<br>• group technology<br>• Task orientedFlexibility<br>• modularity<br>• scalability<br>• integrability<br>• adaptability<br>• rapid tuning<br>• multi tasking | • Economy improvement<br>• Cost holistic<br>• Cost optimization development<br>• Cost intelligent optimization development | • Process off-line diagnosis and errors decreasing<br>• Errors off-line model based recognition and compensation<br>• Errors control basing on previous operations, [YeYong] and reference points<br>• Positioning and setup precision development | Process efficiency<br>Object process<br>ACO based |
| • Flexibility focus onintelligent reconfigurability<br>• cellular reconfigurability<br>• machine reconfigurability<br>• autonomous machine system<br>• autonomous cellular system<br>• autonomous intelligent machining<br>• positioning and setup optimization<br>• Holistic flexibility | • Cost holisticintelligent optimization | • Errors on-line recognition and in tool path compensation<br>• errors self control<br>• error free workpiece<br>• defects free machine<br>• self healing machining | On line optimal<br>• self control<br>• self optimization<br>• time optimal machining<br>• cost optimal machining<br>• holistic optimal machining |

Control problems relating to machine tool and machining process virtualization, the solution of which determines the realizability of an intelligent machining module, were thoroughly examined by Kadir [8] who analyzed the architecture of a virtual CNC system and hardware in the machine tool feedback loop (Fig. 3). His CNC model integrates CAD/CAM, cutter location file interpretation, tool path generation with process dynamics taken into account, axis motion control tracking, feed drive servo, positioning and feedbacks. The model enables the real-time identification of noise parameters and positioning errors.

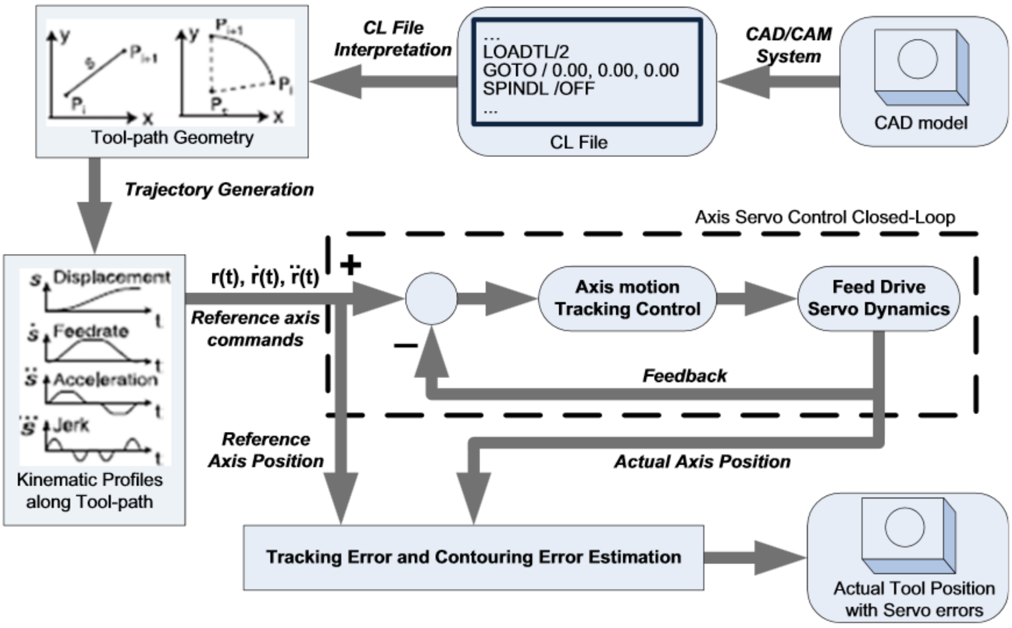


Fig. 3. Architecture of virtual CNC system [8]

Kadir also indicated that the new HIL (Hardware In the Loop) simulation strategy, integrating the virtual machine tool with the software environment in the control system, enables the computation of machine tool dynamics in real time (Fig. 4). This consists in continuous improvement, but makes it easier to integrate the machine tool with the PLC.

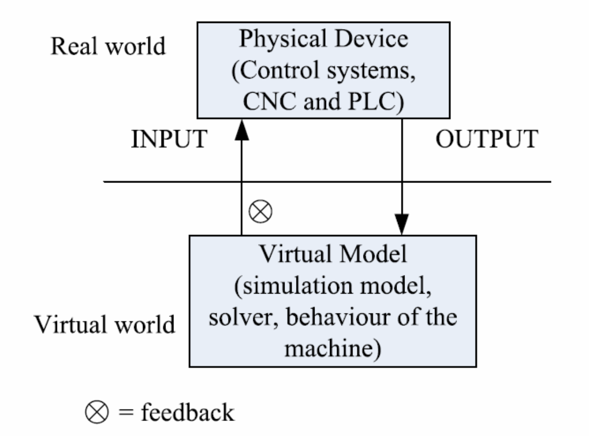


Fig. 4. Hardware-in-the-loop simulation for machine tool [8]

Currently simulation is based mainly on the STEP-NC (Standard for the Exchange of Product model data for Numerical Control) standard and the improved object data model with a high-level language (e.g. C++ or Java) used to describe the data and the kinematic structure of machine tools. The model greatly facilitates programming and opens up the possibility of implementing intelligent functions. The first industrial prototype of STEP-NC as applied to the Siemens 840D controller was developed by WZL Aachen.

Recently STEP-NC has been significantly improved in South Korea and it comprises five modules [11]:

- shop floor programming system,
- tool path generator,
- tool path viewer,
- man-machine interface,
- CNC kernel.

The subsequent research conducted in Germany, the USA, Switzerland and France was aimed at creating an intelligent controller. The research is still underway today.

STEP is an ISO standard for the transfer of CAD/CAM data and it applies to all product data. Figure 5 shows the information defined in this protocol through Application Protocols using the EXPRESS language [6]. STEP-NC for 3D data was created in 1990. It communicates with CAD, CAM, CNC and the machine tool through appropriate interface standards, also subject to continuous improvement.

Conventional programming based on the G code, and high-level intelligent programming based on STEP-NC, enabling the realization of intelligent functions and the tool path (corrected through a feedback with the machining process) in real time [18] are compared in Fig. 6.

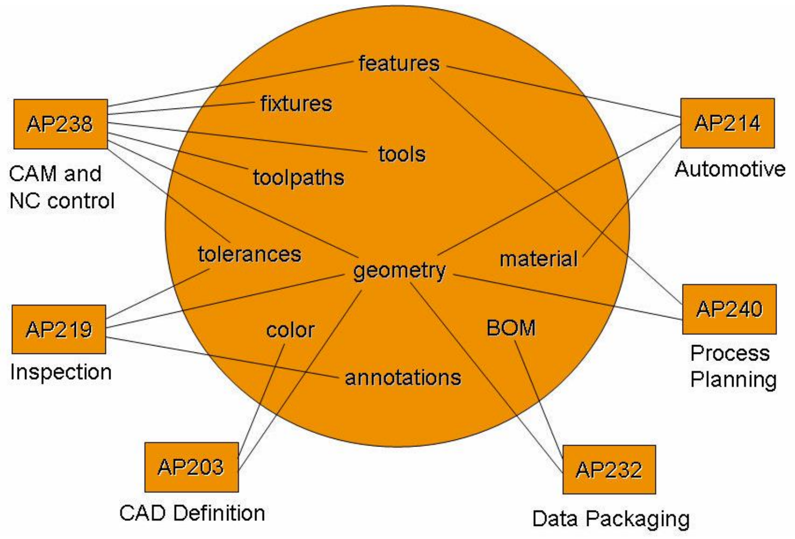
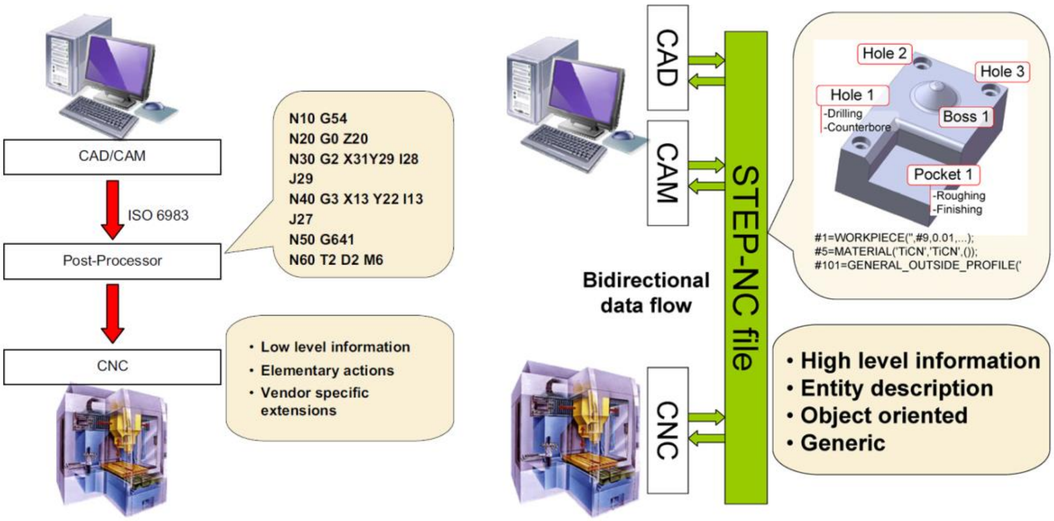


Fig. 5. Information defined by STEP for manufacturing [6]



```
N10 G54
N20 G0 Z20
N30 G2 X31Y29 I28
J29
N40 G3 X13 Y22 I13
J27
N50 G641
N60 T2 D2 M6
```

```
#1=WORKPIECE(",#9,0.01,...);
#5=MATERIAL('TiCN','TiCN',());
#101=GENERAL_OUTSIDE_PROFILE('
```

Fig. 6. Current G-code programming [18]

The most advanced form of STEP-NC programming is Adaptive STEP-NC programming, in which the tool path and commands to the controller can be generated on the basis of the process data from the machine tool. Rauch also presented a concept of advanced multiprocessor manufacturing, using STP-NC (Fig. 7) [18].

Figure 8 shows a concept of the complete architecture of an intelligent STEP-NC controller based on a multiagent system [11]. Since this intelligent controller is to be supported by 14 agents there is still a long way to go before it is applied in industry considering that the definition of the structure and functions of the agents, as standards, requires many studies. Figure 9 shows actual benefits from the use of STEP-NC [10].

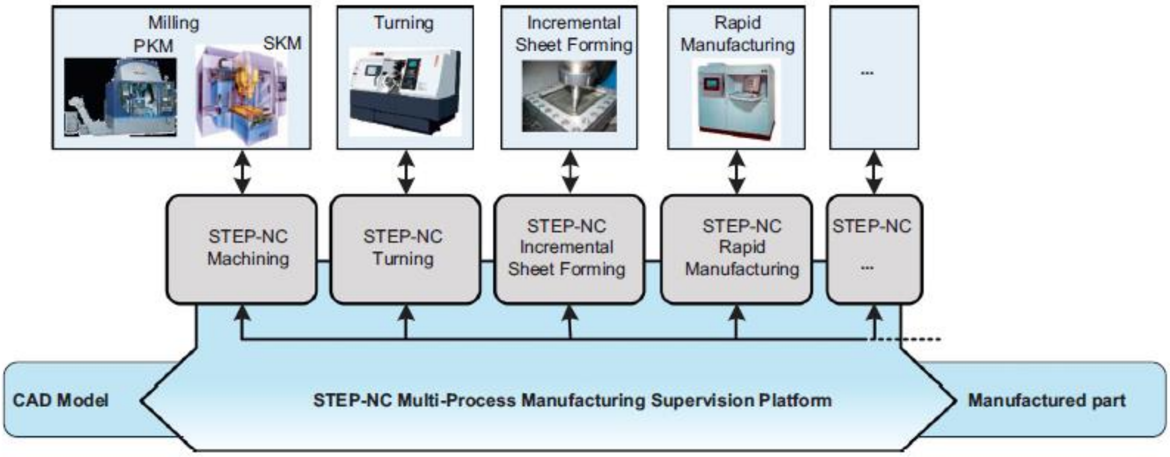


Fig. 7. STEP-NC multi-process manufacturing concept [18]

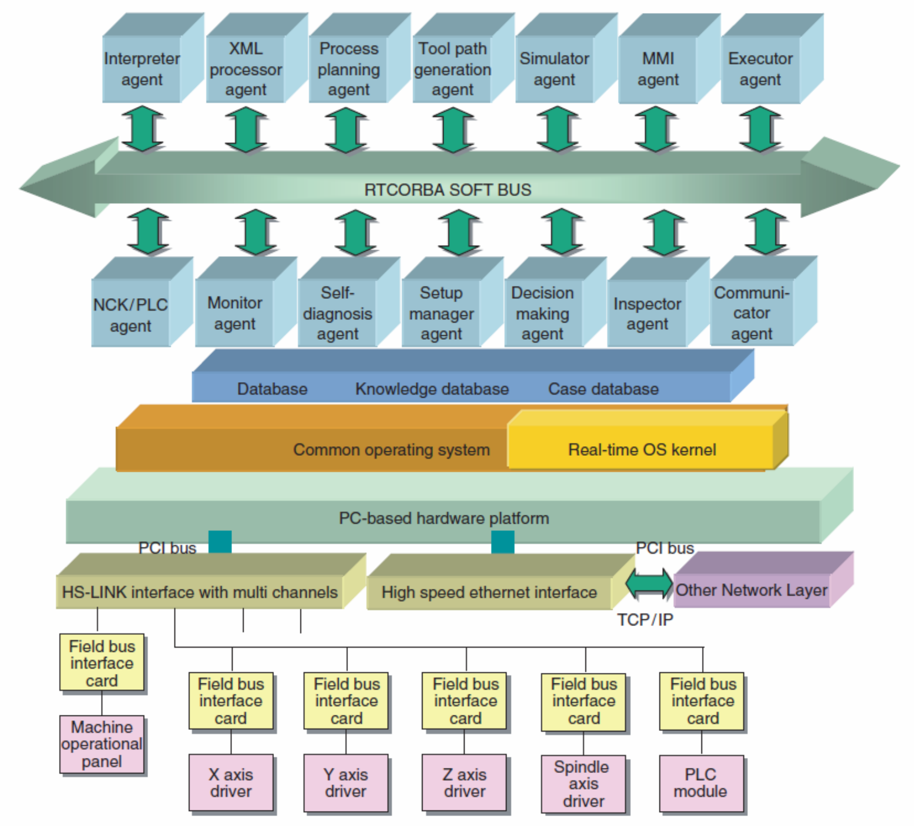
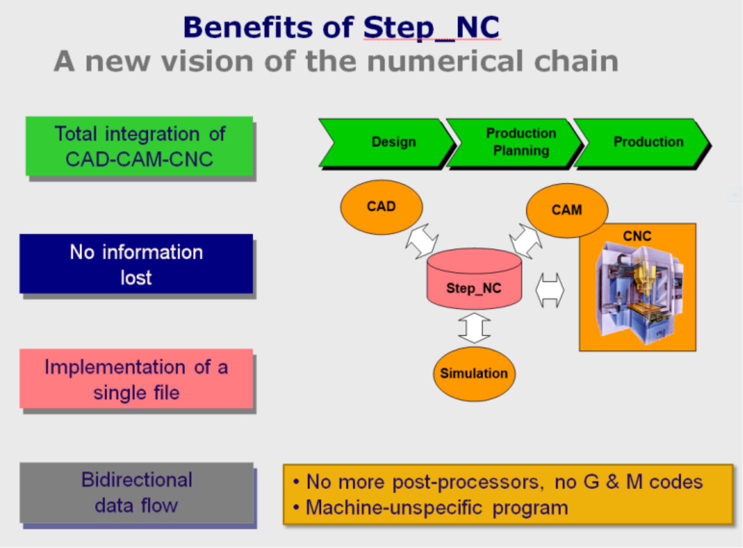


Fig. 8. Architecture of multiagent-based intelligent STEP-NC controller [11]

The insufficiently complete machine-tool model continues to be the shortcoming of virtualization. The considerable progress made in the virtualization of the machining process and its dynamics was reviewed by Altintas [2], who indicated that the accuracy of virtualization depends mainly on the accuracy of the prediction of cutter-workpiece engagement conditions and that this should be the subject of intensive research.



**Benefits of Step_NC**

**A new vision of the numerical chain**

Total integration of CAD-CAM-CNC

No information lost

Implementation of a single file

Bidirectional data flow

- No more post-processors, no G & M codes
- Machine-unspecific program

Fig. 9. Benefits from STEP-NC use [10]

Currently, control systems solutions enabling the quick in-line prediction of vibration and the quick optimization of the process parameters (spindle speed and feed rate for the milling operation) are intensively sought. A schema of such a system was proposed by Bosetti [3] (Fig. 10) who showed how optimal process control sequences can be calculated in an analyser on the basis of a machine tool and process dynamics model and the monitoring signal, taking into account the adaptation of the natural/active parameters of the process. At the output there will be, e.g., the optimal cutting time, the surface texture and the tool wear, i.e. the process free of chatter as a result of the computational analysis of SLD (the Stability Lobes Diagram). The analyser determines the stability limit for the receding horizon (actual chatter frequency F). The chatter recognition procedure shown in Fig. 10 has all the hallmarks of intelligence.

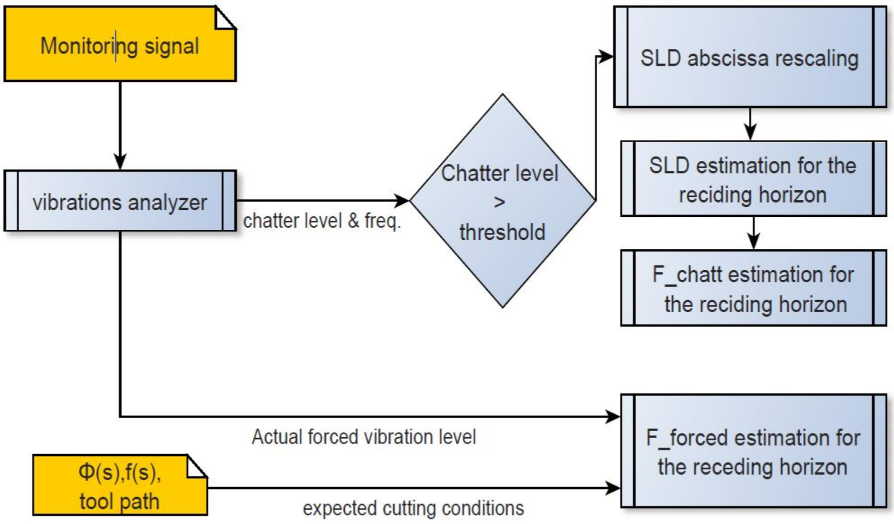


Fig. 10. In-line vibration prediction schema [3]

## 3. INTELLIGENT FUNCTIONS

As mentioned above, the accurate recognition of the machine and process status is the basis for making rational decisions ensuring that the machining process runs smoothly. The more complex the machining processes and the machine tool operation disturbance processes, the greater the complexity of the mechanisms of their accurate recognition. Park [15] presented a concept of efficient autonomous manufacturing aided by an agent system. The cognitive agent architecture proposed by Park is shown in Fig. 11.

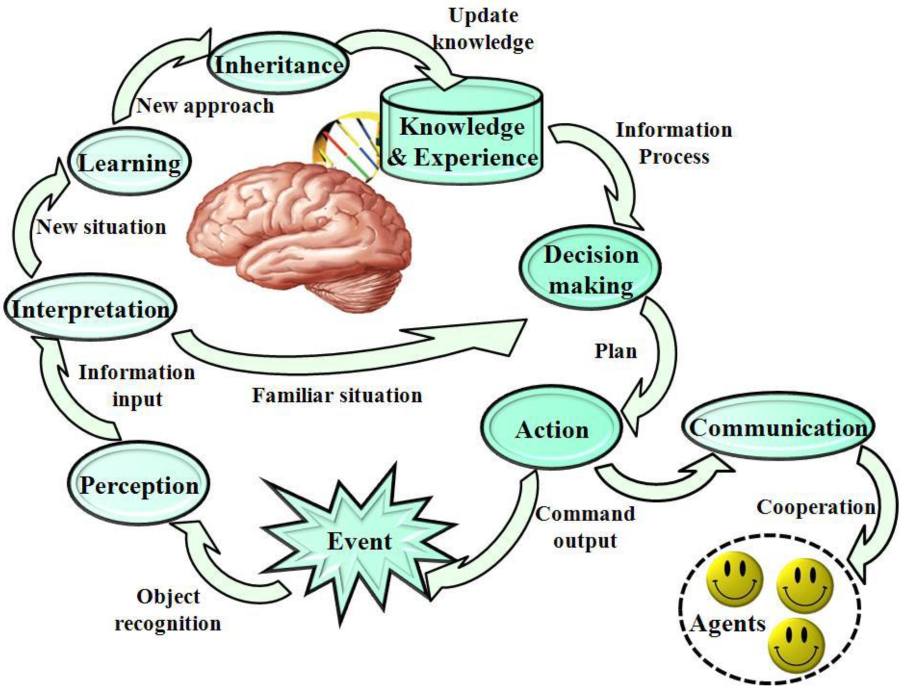


Fig. 11. Architecture of cognitive agent [15]

The presented sequence of actions based on knowledge enables decision making based on the sequence of processes taking place in the human brain during the observation of an event. The recognition of the latter is possible owing to perception, which generates a preliminary piece of information subject to interpretation as a result of which the perceived situation is classified as belonging to a set of familiar situations or a set of new situations. In the case of a new situation, a new approach must be proposed, for which the learning process is used. Then the links with the past (the inheritance of characteristics) are analyzed and the accumulated knowledge is updated. Thanks to the updated knowledge proper decisions on actions to be taken can be made also in the case of new (unfamiliar) situations. The aim of the actions taken through communication and collaboration with the other agents is to properly respond to an event to counteract adverse effects or to improve specific properties. The same processes should take place in an intelligent machine tool as a result of the observation of disturbances to the assumed correct machine tool operation.

## 4. LEARNING

Learning plays an important role in the intelligent machine tool, and also in the intelligent realization of machining processes and generally in manufacturing. It is used in all the stages of the production process for its optimization. The ability to learn is an inherent feature of the theory of intelligence. Learning is needed in order to:

- digest and synthesize information into knowledge,
- support the decision process.

Learning can be divided into deductive learning (analysis) and inductive learning (synthesis). Learning leads to new knowledge. Discovery is achievable for the autonomous version of the manufacturing system. Learning through observation (the tracking and comparing of effects) and experiments is very useful in production.

The use of learning in manufacturing was analyzed in [13]. Table 2 shows an attempt at a comparison of six principal learning methods applicable in manufacturing and their basic characteristics. Considering their properties, the usefulness of the particular methods depends on many factors, such as: type of available information, available knowledge, recognized patterns, human commitment, etc. The possible applications of learning are presented in Table 3.

Table 2. Key properties of learning approaches [13]

| Properties<br>Learning methods | Uncertainty handling | Robustness | Representation power | Explanation | Generalization | Discovery |
|---|---|---|---|---|---|---|
| Symbolic classification | ▓ | ░ | ▓ | █ | ▓ | ░ |
| Explanation based learning | ▤ | ░ | ▓ | █ | ▓ | █ |
| Discovery & analogy | ▤ | ▓ | █ | ▓ | █ | █ |
| Pattern recognition | ▓ | ░ | ▓ | ░ | ▓ | ░ |
| ANNs | █ | ▓ | ▓ | ░ | ▓ | ▓ |
| Neuro-fuzzy | █ | ▓ | █ | ▓ | ▓ | ▓ |

Table 3. Requirements of application domains [13]

| Learning methods<br>Application domain | Symb. classification | Expl. based learning | Discovery & analogy | Patern recogntion | ANNs | Neuro-fuzzy |
|---|---|---|---|---|---|---|
| Design | █ | ▤ | ▤ | ░ | ▓ | ░ |
| Process planning | █ | ▤ | ▤ | ▤ | ▓ | ▓ |
| Production mod., mon., contr. | ░ | ▤ | ▤ | ▓ | █ | ▓ |
| Insp., diagn. & qual. contr. | ░ | ▤ | ▤ | ░ | █ | ▓ |
| Production pl. & control | ▒ | ▒ | ▤ | ▤ | ▓ | ░ |
| Robotics & assembly | █ | ▤ | ▤ | ▓ | █ | ▓ |

| ▤ | ░ | ▓ | █ |
|---|---|---|---|
| Not characteristic | low | middle | high |

The approach to learning changes with: better acquisition of information about the status of the machine tool and the process, greater access to current knowledge, intelligent manufacturing strategy development, and better learning process organization.

In the case of machine tools, the acquisition of information about the status of the machine tool and the product/part in real time plays a vital role. This is the subject of research conducted by Denkena [4], which is devoted to both gentelligent components for machine tools and the intelligent machine tool and machining concept.

## 5. EMERGING CONCEPTS AND COMPONENTS OF INTELLIGENT MACHINE

As part of research [5] conducted in the Collaborative Research Centre at TU Hannover a concept of integrating the “feeling” of the workpiece and the machine tool with adaptive control by means of new-generation sensors was formulated. The major elements of this concept are the creation of sensors which will not influence the static and dynamic properties of the machining system and the solution of the problem of effective communication between gentelligent components. Integration also applies to the acquisition of information about the properties (history) of the components, the direct processing of information, and the planning and control of the machining process. Thus it is a concept of the effective and intelligent determination of individual machining sequences, based on knowledge which takes into account the manufacturing environment (factory) requirements (Fig. 12) [19].

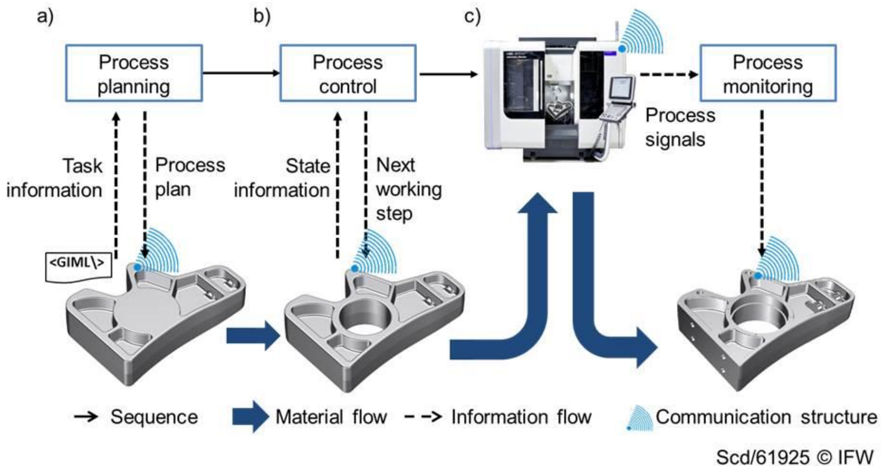


Fig. 12. Planning and control of gentelligent production [19]

According to this concept it will be possible to track the properties of gentelligent components in their whole life cycle. By developing this concept one will come closer to the planning of the intelligent maintenance and repair of the process in which such components are used [4].

Also an individual approach to each part being manufactured or developed and knowledge of its history and movement/path from the manufacturer to the customer are of major importance in contemporary manufacturing engineering. This kind of identification is practised and documented (in an easily accessible way) in the aviation industry and necessitates the labelling of parts. According to the gentelligent concept, the properties of a component are to be tracked through RFID (Radio Frequency Identification) using built in devices and sensors, whereby it will be possible to monitor the status of parts over time and maintenance, repairs and storage will be facilitated. If parts/products acquire the ability to communicate with the environment and are able to send information about their current properties, they will have the hallmarks of intelligence. The information could include machining process data, such as: loads, accelerations and temperatures, acquired in real time directly from microsensors/multifunction sensors.

The implementation of this concept can also significantly contribute to the protection of property rights and the correctness of product manufacturing, assembly, service and development. It can also be a source of information about the current quality of the component, used for the optimal control of its operating properties. Figure 13 illustrates the concept of the planning and machining of *gentelligent components* [4].

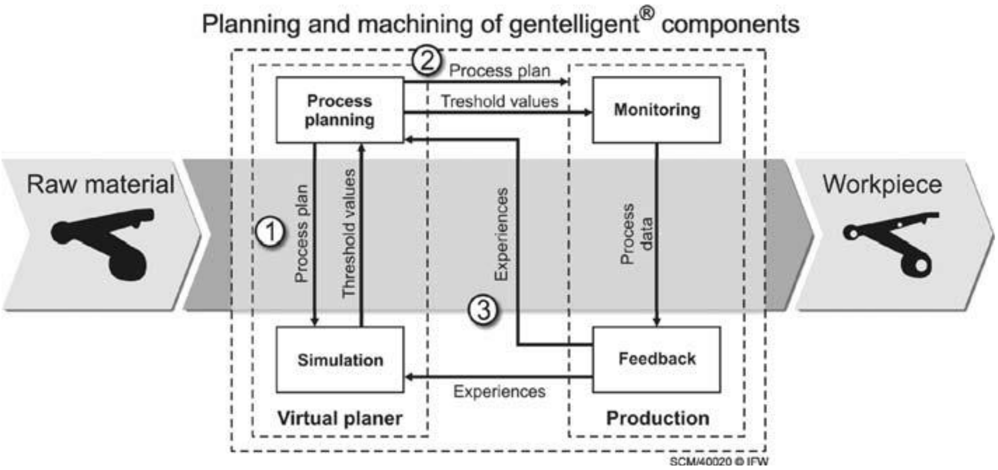


Fig. 13. Concept of process planning and machining *gentelligent components*, based on simulation, monitoring and feedback [4]

The future of the intelligent component, product or manufacturing process, proposed by Denkena, depends not only on the creation of its efficient monitoring and status evaluation modules, but also on efficient control and optimization in real time. In the case of the virtualization of the cutting process realized in the above (or similar) way, the monitoring of the forces [5] and temperature on the tool point [21],[28] is of key importance. The monitoring can be conducted in an intelligent way, whereby it will be more effective. If fully implemented, the *gentelligent components* concept will constitute a highly promising basis for the future intelligent machine tool.

For monitoring the temperature of the end mill tool point Shindou [21] used an Infrared Ray Technology thermographic camera H2640 made by Nipon Aviation, with a spatial resolution of 0.6 m/rad and a temperature resolution of 0.03°C, able to perform measurements up to 500° (the camera was used at a milling cutter speed of 1450 rpm). This is mentioned here since the above technology (Fig. 14) is extremely precise and the measurement is conducted continuously in real time, but only in the case of dry machining. Owing to its high in formativeness this temperature measuring technique is suitable for intelligent monitoring.

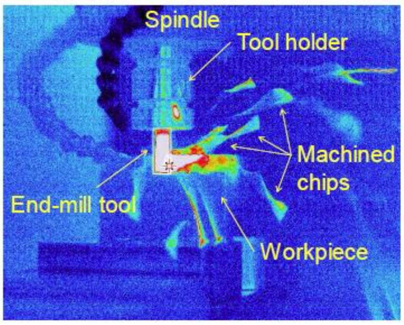


Fig. 14. Infrared imagery of end-mill process [21]

The intelligent avoiding of collisions is one the badly needed intelligent functions of the machine tool. A noteworthy concept of this function was developed by Ahmad [1]. It consists in the simulative determination of the collisionless trajectory of the tool on its way to the workpiece in a multitasking machine tool. It was shown that a collisionless tool trajectory can be intelligently planned in real time at minimized distance and time. This was achieved by feeding spatial signals from three vision cameras into CAD and CAM systems with a feedback and then directly into the CNC, bypassing the postprocessor when STEP-NC is used. Three approaches were compared. The first procedure of avoiding collisions is based on a program written into the postprocessor. The second procedure is based on the tracking of tool movement through camera image processing and on the tool trajectory written into the postprocessor. The third procedure (Fig. 15) is based on camera image processing.

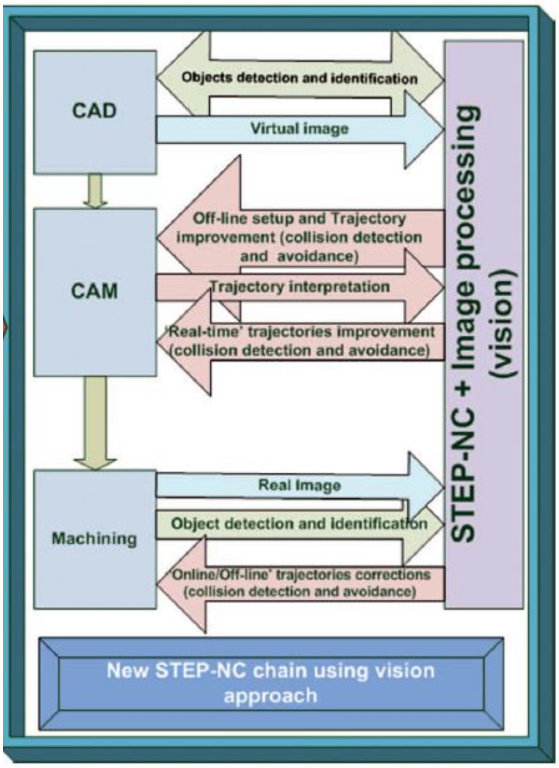


Fig. 15. Vision-based approach integration in new and conventional production chain [1]

The STEP-NC system enables tool trajectory correction in real time in an intelligent way. This is possible if an appropriately high vision signal processing speed is achieved. The research on the above method was based on a detailed analysis of the factors contributing to collisions on the tool path to the workpiece in the multitasking machine tool. It was shown that collision prevention must be based on the accurate recognition of the variable dimensions and geometry of the constant machining system components and assemblies and the movement dynamics. Ahmad [1] distinguishes two types of collisions: virtual and real collisions. Collisions can be most effectively prevented when the relevant procedures are intelligent and the collision possibility recognition is also intelligent. Moreover, the accurate transfer of information, also based on AI, must be highly reliable considering that there can be disturbances originating from the controller software, the environment, the service, the virtualization, etc.

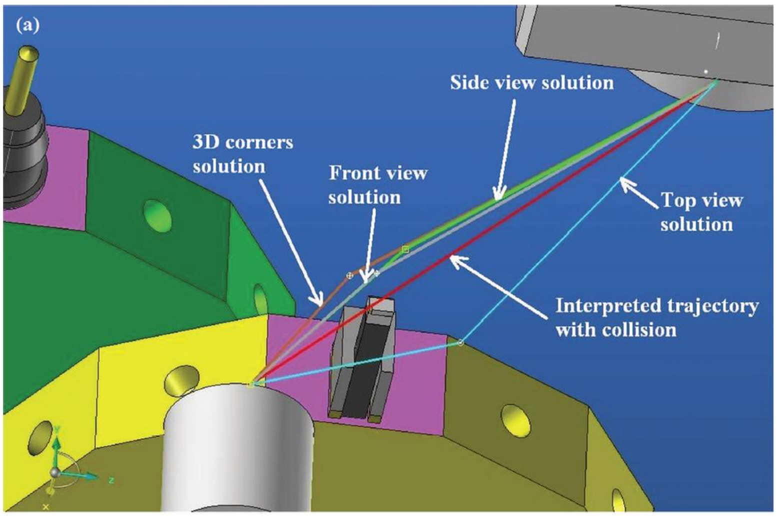


Fig. 16. Trajectories in 3D (RESIT algorithm) [1]

Many other works on multiaxis machine tools and 3D space deal with the generation of a safe (collision-free) trajectory, aided with vision cameras and CAM data. 3D collisionless trajectories can be determined using virtual orthogonal 3D projection (Fig. 16) and 3D data processing by the RESIT algorithm. At the moment such trajectories can be determined only off-line in about 5 and 2 sec in the case of respectively 3D and 2D projection.

## 6. REAL TIME ACHIEVABILITY

Currently attempts are made at continuous machine tool status and machining process correction and error compensation in real time, which is particularly necessary in the case of (large) thermal errors caused by thermal deformations in the controllable axes of machine tools, especially HSC machine tools with required high (micron) machining precision.

So far, off-line error compensation, performed during breaks in cutting, without continuous tool trajectory adjustment or compensation consisting in error prediction and writing corrections into the trajectory during its design is practically available. Error values are determined through measurements or modelling and numerical simulations on the basis of regression functions, fuzzy logic, artificial neural networks or using other mathematical apparatus. Compensation corrections are collected in tables and data clouds or generated online.

Recently studies aimed at continuous tool path correction during the machining process by introducing compensation at the end of a path segment whose length corresponds to the interpolation resolution (approximate interpolation is sufficient for this purpose) have appeared. In studies presented in [20] the length of the interpolation segment was 0.0002 mm at a 12 m/min rate of feed along the controllable axis when the interpolation period was about 0.001 s. In order to lower the above values, i.e. to increase compensation precision or machining efficiency, precise interpolation, i.e. with interpolation segment lengths in the order of nanometres (2 nm are achievable), is necessary. This cannot be done without real time. In [20] asynchronous assigning of corrections and an asynchronous data table were used to achieve pseudocontinuous compensation. As a result, error compensation of 70-95% was achieved. This means that one can come closer to the online correction of machine tool and process errors when the dynamics of changes in errors/disturbances are low. A fully intelligent machine tool performing much more complex motion and machining functions (influencing process dynamics, active error compensation) must perform the functions in real time. An exemplary structure of such compensation of the thermal error of a two-spindle rolling guide grinding machine, based on off-line error simulation, is shown in Fig. 17.

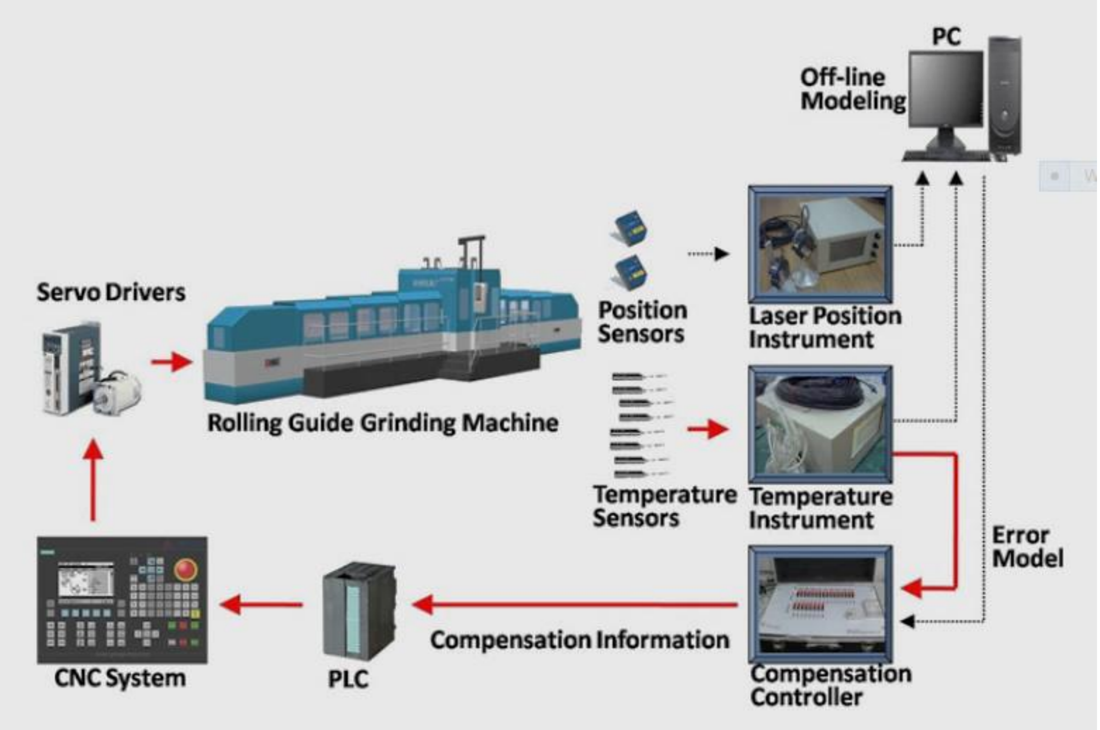


Fig. 17. Off-line modelling and online compensation structure [20]

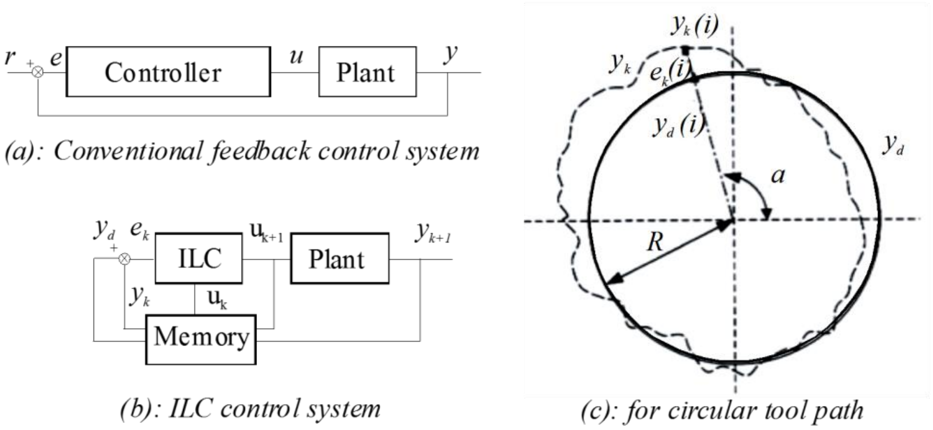
The error model was created on the basis of measurements of spindle axial displacements and temperature in selected points of the machine tool. The information for compensation was in the digital form.

## 7. PRACTICAL REALIZATION OF INTELLIGENT MACHINE TOOL CONCEPT

The incorporation of intelligent functions into the CNC machine tool structure has been the subject of numerous studies. A concise review of the studies against the background of the development: of machine tool software, the openness of control systems and rapid CAM was presented by Ramesh [17]. Machine tool intelligent functions are realized through software, but the control system must ensure the reliability of the functions both through hardware and software. Hence it is said that an intelligent controller very open to the incorporation of modules performing highly complex and time critical operations is needed for this purpose. This particularly applies to machine and process recognition, learning and adaptation to current states for carrying out machine tool tasks and taking optimal and critical decisions (on error correction and compensation, collision and damage prevention, etc.). This is done on the basis of the information about the machine and process status.

The aim of intelligent functions is to increase the autonomy of the machine tool so that the latter on its own can counteract any adverse changes in the operating properties and eliminate the necessity of the (often unreliable) intervention by the operator. As one moves from CAD, through CAPP and CAM, to CNC and the machining process, the operator’s competence decreases and the need to automatically replace it with machine tool artificial intelligence increases.

The basis for the intelligent operation of the machine tool are its modules for: disturbance recognition and handling, taking decisions on the generation of a correct workpiece contour and machined surface geometry and dimensions and ensuring machining process reliability and optimal control. Most diagnostic functions must be performed in real time. They include the analysis and processing of the signals supplied from the sensors, and inference and learning for diagnosis result and automatic supervision decision specification. The monitoring covers forces, speeds, accelerations, jerk, vibrations, temperatures and movement generation consistency with the tool path creation strategy. The above operations must be based on knowledge, including correction prediction, taking into account the required precision of positioning in the particular rotational and feed axes. Then intelligent decision taking and the control of movements in the axes take place, including machining result feedback. Attempts are made to use the intelligent STEP-NC standard [9] and the iterative learning approach (Fig. 18) [14]. A P-type learning algorithm which introduces the command signal in the form of learning, taking into account the input and output error (e.g. positioning error from the preceding operation), into the machine tool and tracks the correctness and repeatability of the tool trajectory (error compensation) was adopted. An ILC (Iterative Learning Control) algorithm calculates (using the C language) the correction and through an ancillary error interpolator synchronized with the main interpolator sends it to the machine tool. In this way radius error $y_k$ was reduced from 47°μm to 4.1°μm.



(a): Conventional feedback control system

(b): ILC control system

(c): for circular tool path

Fig. 18. ILC and feedback control system [14]

A concept of an autonomous intelligent machine tool (Fig. 19) based on such modules as mentioned above was presented by Shirase [23]. In this solution the tool path during the active milling of the contour defined by CAD is generated in real time without the participation of the NC program.

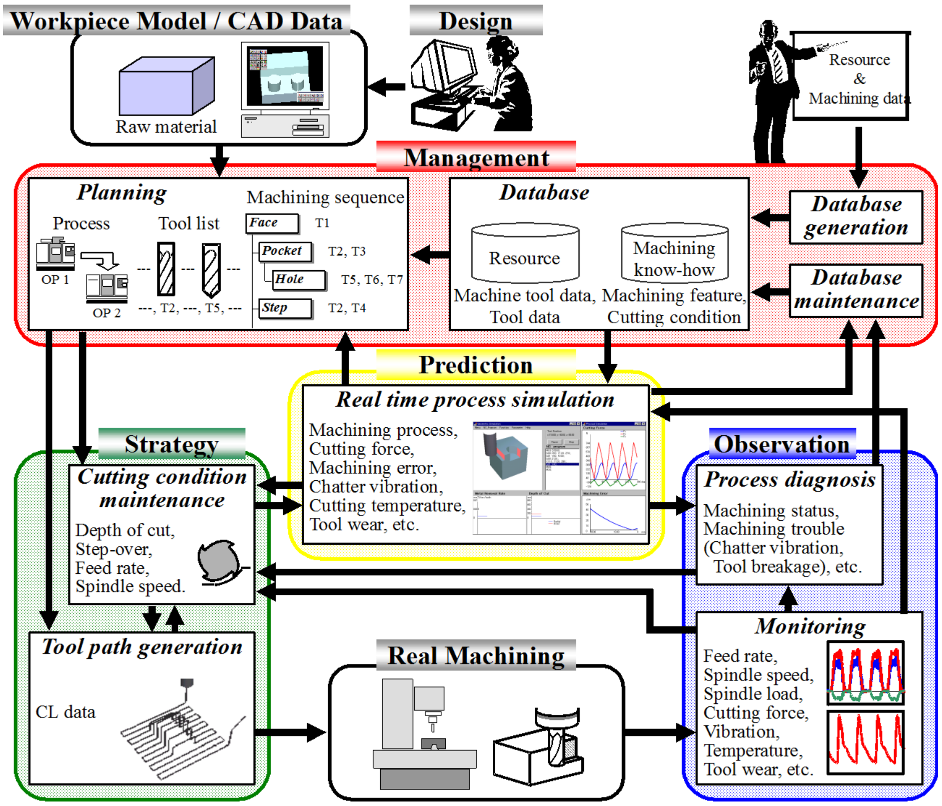


Fig. 19. Conceptual structure of autonomous and intelligent machine tool [23]

For this purpose a concept of the digital tracking of the outline of a 3D CAD workpiece model, integrated with the process planning and the course of milling, was developed. The planning process was aided by a special program (the Mill-Plan) developed by Toyota. The process was supervised by simultaneously tracking the simulated and measured cutting force.

The control system of the conventional machine tool comprises a controller for tool path generation and positioning control, an actuator incorporating a servo drive and an amplifier, and the machine tool itself ensuring movements in the controllable axes and performing cutting. There are two feedbacks: one between the machine tool and the servo and a interpolation feedback between the machine tool and the NC. The intelligent machine tool includes a computer which plans the process and generates the tool path in real time, using a database and a knowledge base as well as information about the machining process and its results. The machining process is here an important component module and the tooth path is generated without the participation of an NC program. The procedure is shown in Fig. 19.

In the exemplary intelligent machine tool shown in Fig. 20 there is a feedback between the servo and the DCM (Digital Copy Milling) and a feedback between the machine tool and the DCM. In other words, there is a feedback between the process and the NC and a feedback between the process and the tool path generating computer. The presented example is for outline copying. The generation of a tool path and commands during machining is illustrated here for digital copy milling based on the virtual simulation of tool movement. In the computer the virtual probe model tracks the workpiece model and generates a tool path. Adaptive control and detection of an abnormal increase in the cutting force, as a symptom of the onset of tool point chipping, are ensured. The significance of this concept consists in the fact that it was realized by choosing a relatively simple example of copy milling, creating its digital model used in real time and implementing supervision in real time. The digital CAD-3D model was integrated with the digital CAPP (Computer-Aided Process Planning) model, the DCM (Digital Copy Milling) and the servo. A feedback between the servo and the DCM and a feedback between the machining process and the DCM in real time were implemented.

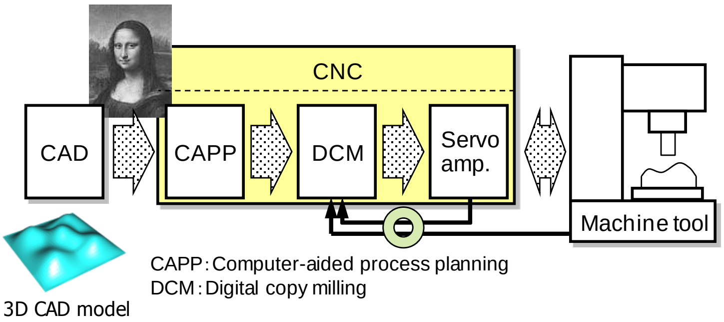


Fig. 20. CAM-CNC integration for intelligent and autonomous NC machine tool [23]

Thanks to the implementation of this intelligent machining concept the necessity of using the rigid NC program was eliminated while the adaptive control made possible the continuous adjustment of the machining conditions, depending on the forces acting on the cutting tool. Also the tracking of machining process course correctness was made possible and the flexible planning of the process in real time was implemented.

## 8. APPLICATIONS DEVELOPED BY MACHINE TOOL MANUFACTURERS

Many manufacturers of machine tools in order to improve the operating properties of the latter try to introduce intelligent functions. This is mainly dictated by the necessity to make error compensation more efficient and to increase the effectiveness of preventing collisions, chatter and excessive energy consumption. This requires the accurate identification of the improvements introduced in this way and a thorough evaluation of the benefits for machine tool users. The priorities are: cost reduction and increasing reliability, lifetime and the efficiency of machining processes. Since intelligent functions enhance the marketability of machine tools their manufacturers highlight the achieved benefits in their publications and commercial brochures. A fine example of the promarket application and appreciation of intelligent functions is the Yamazaki Mazak Corporation [25] which stands out in the promotion of its achievements in this field. The achievements include:

- the active control of vibrations by means of the MAZOTROL CNC control system and the finite impulse response filter;
- the use of an intelligent thermal shield, to be more precise, the efficient compensation of errors by means of the displacement response surface (Fig. 21);
- the use of an intelligent safety shield to prevent collisions;
- the use of an intelligent efficiency shield to prevent machine interference mostly in multitasking machining;
- the introduction of voice help;
- intelligent aiding of personnel through comprehensive behaviour monitoring;
- the use of an intelligent balancing analyser to prevent considerable machine down time;
- bar feeding control in the lathe.

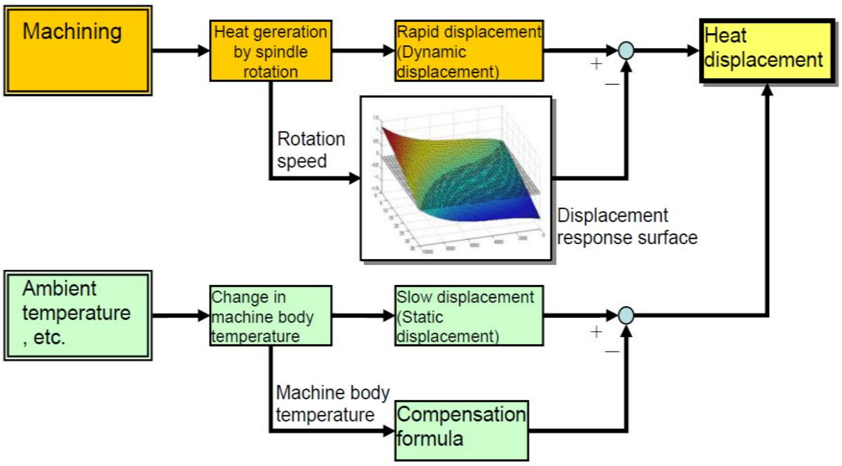


Fig. 21. Intelligent thermal shield system chart [25]

These are software- and hardware wise complex procedures which effectively improve the operating properties of machine tools and their productivity. Many of the above measures have been adopted by other machine tool manufacturers, e.g. OKUMA, DMG Mori and Makino.

As regards Fig.º21, it should be noted that in its controllers MAZAK uses compensation corrections for slowly-varying thermal displacements, defined as the product of the measured temperature and an appropriate coefficient.

In the case of quickly-varying thermal displacements which occur when the rotational speed of the spindle changes, in the MAZAK Corporations corrections are determined on the basis of the displacement response surface expressing the dependence between the thermal displacement of the spindle along its axis, the rate of displacement changes and the rotational speed of the spindle. The method is described in detail in [25]. Its effectiveness is illustrated, e.g., by the fact that the error of 20ºμm was reduced to 7ºμm.

## 9. CONCLUSIONS

A review of the major (in the authors' opinion) achievements contributing to the creation of intelligent machine tools was carried out in this paper. In comparison with the expectations presented in the Introduction a significant step towards the transformation of the conventional CNC machine tool into an intelligent machine tool has already been made. The development of control systems and software and that of the digital simulation of machine tools, control systems and processes proceed in this direction. Also monitoring, error simulation, collision simulation and error correction systems assume an intelligent form, especially when the activities can be conducted in real time.

In the case of simple machining processes characterized by relatively low dynamics it is now possible to plan and supervise the processes in real time on the basis of approximate interpolation. Today, since there is a need for achieving high productivity, accuracy and cost reduction, real time achievability in machine and process status recognition and process planning and correcting is the main direction of research.

The fact that digital machine tool, machining process and environmental impact model is still incomplete hinders the development of intelligent machine tools. The holistic modelling of the interactions for the purposes of simulation in real time poses a challenge to the present and future research. It is expected that the functions of intelligent self-healing and optimal real time process control on the basis of self-learning will be developed, but this requires some modifications to the approach to modelling.

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