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Machine tool development from high level of holistic improvement to intelligence

J. Jędrzejewski*
Department of Machine Tools and Mechanical Technologies, Wroclaw University of Technology, ul. Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland
* Corresponding e-mail address: jerzy.jedrzejewski@pwr.edu.pl

ABSTRACT

Purpose: The aim of the paper is to identify the research efforts of the coming machine tool improvements towards the intelligent level of development.

Design/methodology/approach: An approach to the machine intelligence will be based on a holistic modelling of machine tool system components and a process generating tool path, digitalization, virtualization and improvement for adaptive control of machine tool and process behaviour in real time.

Findings: Intelligent procedures for machine and process efficiency control based on real time machine and process monitoring, on-line tool path generation, optimization and adaptive control.

Research limitations/implications: A real time reachability for the high speed cutting and achievable computing power for the real time simulation of the tool path generation process.

Practical implications: High efficient manufacturing.

Originality/value: A unique presentation of the state of the art in knowledge oriented on concepts of intelligent machine tools generation as the coming level of development.

Keywords: Machine tool; Holistic; Improvement; Intelligence

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CONCEPTUAL PAPER

1. Introduction

As part of their development today machine tools (MTs) need to be endowed with intelligent functions. The development is governed by the market, particularly by the business demands of the users and the producers. The current development of machine tools is dictated by the highest possible efficiency, whereby MTs must be characterized by high dynamics, precision and technological flexibility as well as by ever higher reliability, environment friendliness (including ever lower energy consumption) and increasingly lower cost intensiveness of both the machine tool and the machining process. Also the production jig (being, similarly as MT, a mechatronic device), which automates workpiece positioning and fixing, has a significant bearing on manufacturing/machining efficiency. It is equally subject to improvement as the machining tool.

In order to meet so complex requirements the complexity of the machine tool machining system and consequently the complexity of disturbances in its proper/required performance in the operating conditions constantly increase. Because of the complexity and time-variation of disturbances and errors and the complexity of measures aimed at reducing and compensating them one must use highly advanced fundamental knowledge and knowledge relating to modelling, numerical simulation, optimization and control.

In order to effectively identify disturbances and their causes and to counteract, minimize and control them as well as to compensate the errors generated by them one must do it intelligently. The functions of MT and the whole machine tool system should be gradually aided with an ever larger number of intelligent procedures. The future development of machine tools will be determined by the improvement of intelligent procedures imitating intelligent actions taken by the human being. Also the future holistic improvement will be aided with intelligent procedures enabling a substantial increase in machine tool excellence and opening up new possibilities for creating a completely new concept of machine tool operation.

The use of artificial intelligence (AI) to solve complex manufacturing problems has been the subject of numerous studies dealing with the concept of intelligent machining systems and their modules. In the 1990s many works on this subject were published by the members of the International Academy for Production Engineering (CIRP), in particular:

- K. Ueda's studies (1992, 1997, 2001, 2006, 2014) on biological manufacturing systems;
- the keynote paper by H.P. Wiendahl, G. Sohlenius, (1994), devoted to the management and control of the complexity of machine tool systems;
- H.J. Wareneke's work (1993) presenting a fractal factory concept.

Also the numerous papers by D.H. Kim, (2003, 2005, 2006, 2009), describing the interactions between machine tools (M2M) in the machining system, performed through modelling by agents assigned the functions of: dialogue, inference, sensor recognition and communication should be singled out. It should be also mentioned that in 2001 the entire XII CIRP Sponsored Workshop on Supervising and Diagnostic of Machining Systems was devoted to Virtual Manufacturing - edited by J. Jedrzejewski (ISSN 0867-7778 Wroclaw University of Technology). An overview of the research on virtualization was presented in the keynote paper (CIRP) by Y. Altintas, C. Brecher, M. Weck and S. Witt in 2005.

The aim of the present paper was to discuss the steps taken to create intelligent machine tools and the practical achievements in this field, having in mind the necessity to apply intelligent functions in order to significantly improve the operational and business properties of machine tools.

2. Improvement of machine tools

Today quite advanced machine tools are created on the basis of the accurate and partly holistic modelling, numerical simulation and, to an increasing degree, virtualization of their behaviour in their operating conditions and the off-line numerical forecasting and compensation of errors. The achieved relatively high efficiency, precision, technological flexibility, reliability and environmental friendliness of machine tools has its limits due to the incomplete identification and oversimplified modelling of their thermal and dynamic properties, especially in the case of highly dynamic machining processes. Moreover, the development of control systems and software does not keep up with the need for taking phenomena and feedbacks into account in real time. The machining process is planned off-line using a postprocessor and the G function. As a result, the planned tool path differs from the actual one and the control system is unable to promptly respond to disturbances as they arise and affect the machining process.

The improvement of the machine tool's structure, control systems and software plays a major role in the development of machine tools. The improvement of the machine tool's structure involves the use of new materials (including intelligent ones) improving its static, thermal and dynamic properties. The development of the structure aims at ensuring high technological flexibility manifesting itself in the easy adaptability of many hybrid processes (multitasking), including MT reconfigurability. This, combined with the improvement of control systems aimed at increasing their openness and computing and software efficiency, is to ensure the maximum possible autonomy in self-control, the self-recognition of properties and disturbances, self-healing, self-organization and the self-planning of processes, in real time where necessary. To be achievable all the above measures must be based on knowledge, the latest advances in IT and on intelligent procedures.

It is especially important to correct and compensate errors and to prevent failure states. This can be achieved through the intelligent assessment of disturbances and through an intelligent decision process of creating commands for the control of feed in the controllable axis, integrated in real time with workpiece profile generation. This is to be performed on the basis of a numerical path generation model and by correcting the tool path in real time.

In the same way the path of collisionless tool movement towards the workpiece can be generated on the basis of tool path observation or an accurate digital model of the MT work space. In both cases, monitoring and the recognition of errors in real time play the key role. Similar measures are to be used to forecast disturbances in the dynamics of the cutting process within its area, taking into account MT-jig interactions. Special emphasis is placed on solving the above problems, which are crucial for the reliable operation and high efficiency of MTs, especially in the context of the constantly increasing complexity of machine tools and technological tasks. This necessitates highly intensive research on real time achievability and on how to significantly increase the operational efficiency of numerical models and control systems.

3. Continuous improvement and development of MT system

When describing trends in the improvement and development of machine tools one should consider the latter holistically, i.e. together with the production jig control system, the software and the machining process (including the machining parameters and the tool and workpiece behaviour). Each of the components of the MT machining system has a significant influence on the precision, economic and environmental effects of the process and on the operation of MT and the lifetime of its technological efficiency. Although each of the components is subject to individual improvement, the latter must take into consideration the interactions between the components and their joint influence on machining effects.

Therefore, an MT improvement and development strategy should be holistic, i.e. common for the whole system and taking into account its complexity and required behaviour in the operating conditions. However, in practice the particular modules are usually improved separately since there are no adequate software tools enabling the integration of complex models and specialized constituent computing systems into one integrated system of joint numerical simulation of operational properties. The holistic approach requires greater processing capacities and new intelligent capabilities and solutions, which may lead to a new, completely different, generation of bionic machine tools.

In order to describe the current state of MT development aimed at reaching the intelligent level one should present the results of the research aimed at increasing the effectiveness of the improvement in the performance of the particular MT machining system modules through attempts at aiding their operation with applications of AI procedures and by improving as far as possible the properties and structure of the modules in order to facilitate the achievement of intelligent functions. The STEP-NC standard will play a special role here. This applies to all the considered levels of development of MTs (Fig. 1), especially in the area of the improvement of autonomy, reliability and accuracy. The efficiency of the monitoring, identifying and limiting disturbances and the efficient control of healing processes in real time or acceptably close to real time play a major role here. Figure 1 shows that not only the machine tool and the process, but also the jig and the part are subject to development. When describing the basic elements of the MTs development one should also present the strategy of their holistic improvement and the effects to be achieved at each of the higher levels of development.

In order to ensure high precision, reliability and dynamical stability of the machining process special attention is given to the improvement of the static, thermal and dynamic properties through the integrated control of them. This applies to both the machine tool and the production jig with regard to the automation of the precise positioning and fixing of workpieces. Also the improvement in the dynamics of control systems plays a very important role.

In many cases, the basis for the efficient intelligent control of machine tool properties is the accurate forecasting of their states in real time by means of highly advanced software tools, whereby failure states can be prevented and errors can be effectively compensated by holistically taking them into account in the tool path. The forecasting methods must be subject to continuous improvement commensurate with the increasing dynamics of movements and machining processes.

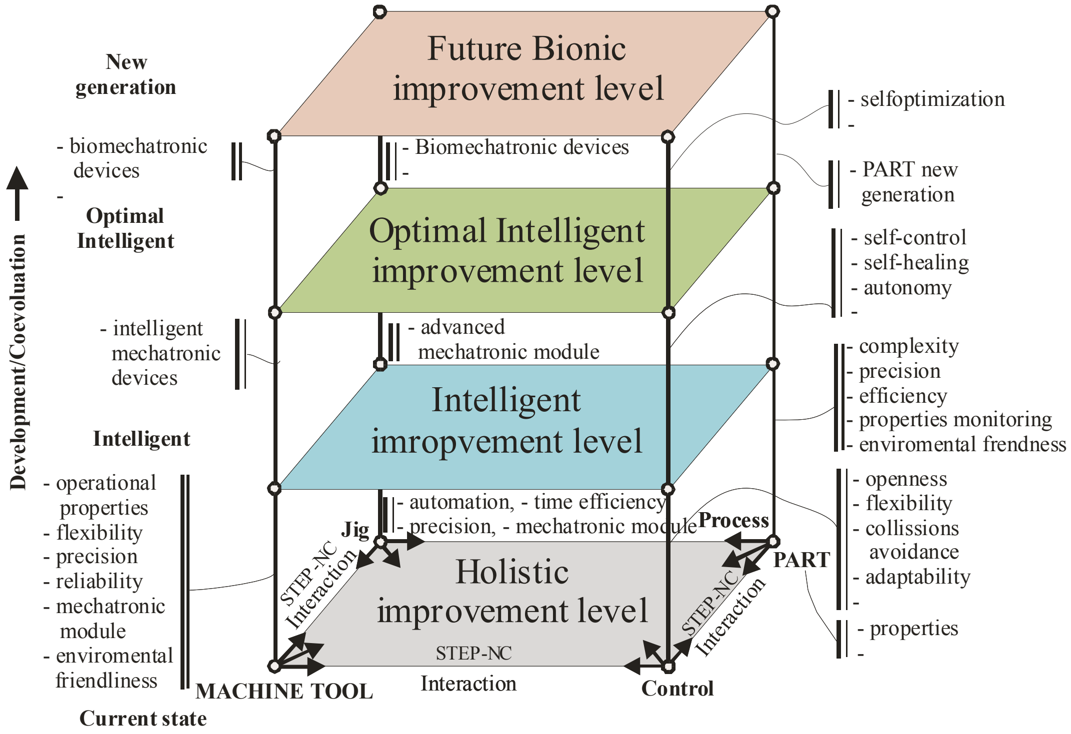

Fig. 1. Levels of machine tools development

4. Characterization of intelligent functions

The model for intelligent decision taking are the functions performed by the human brain. Considering this, H.S. Park [1] proposed the cognitive agent architecture (a sequence of actions ensuing from an observation of an event) shown in Figure 2.

Recognition is made possible by a perception from which preliminary information about the event arises, which is subject to interpretation, and then if a new, so far unrecognized event occurs, the accumulated knowledge will enable decision taking. This is done in consultation with other agents as a result of which an action improving the object's functions or counteracting the adverse effects of the event will be performed. The sequence of actions corresponds to the reaction of the machine tool to disturbances of its properties, which includes taking a decision enabling self-healing.

In the case of the machine tool, information about disturbances is supplied by the monitoring system. The control system decision module will use a knowledge base for its learning process. Learning takes place in various ways which are selected depending on their effectiveness. The ways (methods) [2] include: symbolic classification, analogy, pattern recognition, artificial neural networks and fuzzy logic. The aims are: the determination of uncertainty, robustness and representation power as well as the explanation and discovery of new knowledge. In the case of the machine tool this applies to the minimization of the adverse effects of disturbances through the introduction of appropriate commands into the information (commands) contained in the tool movement path program.

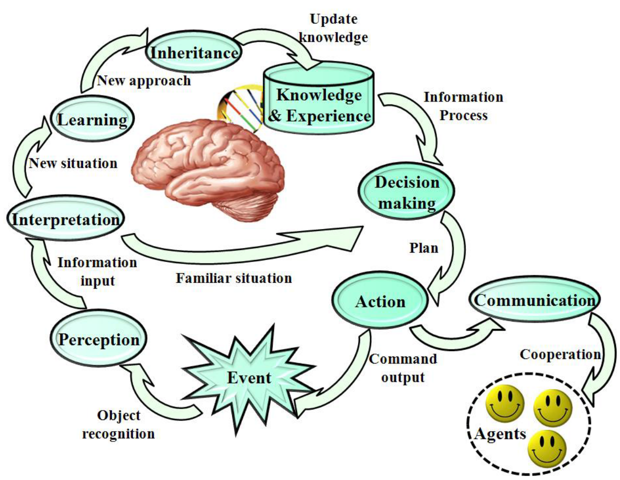

Fig. 2. Architecture of cognitive agent [1]

5. Modelling, digitization and numerical simulation for development of intelligent functions

Intelligent functions bring major benefits since they are based on accurate holistic models of the behaviour of the machine tool, the jig, the controller and the process. An example of a holistic system of modelling and simulation of the static and thermal properties of the machine tool or the jig is the SATO_2 system whose architecture is shown in Figure 3 [3].

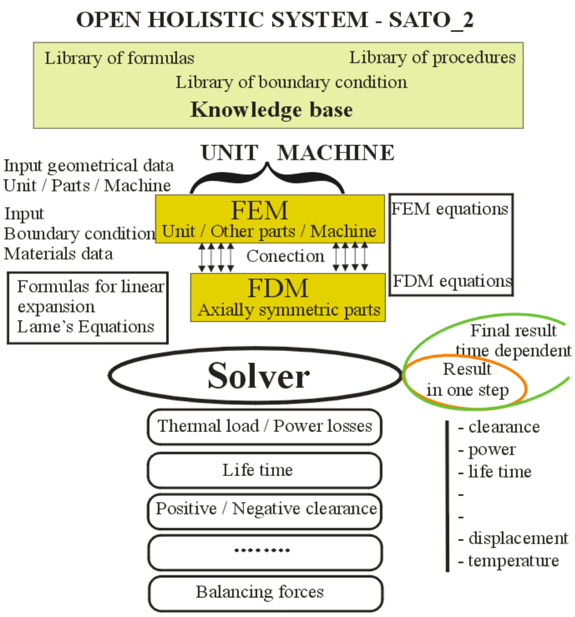

Fig. 3. General architecture of SATO_2 system

On the basis of a database and a knowledge base, including a set of programs, hybrid computing methods, CAD models and data on the assumed operating conditions, the SATO_2 system calculates power losses, clearances in the bearings, the lifetime of the bearings, the temperatures and deformations/displacements as a function of working time, taking into account the interactions between the parts and assemblies of the calculated object. The system is characterized by a high accuracy of the mapping of the processes taking place in real machine tool assemblies, such as headstocks, electrospindles, feed assemblies, rotatory and tilting tables in dynamic states dictated by the operating conditions (changes in speed and loads) during machining and quick feed-in movements.

At present efforts are made to integrate models and computing modules dedicated to assemblies, within systems for computing whole machine tool structures and to fully integrate models and computations of static, thermal and dynamic properties. System SATO_2 comprises a set of models and computing modules. The more accurately all the phenomena and the interdependences between them are taken into account in digital modelling, the more faithfully the natural behaviour of the machine tool can be simulated. An accurate model also enables the accurate forecasting of disturbances and errors and constitutes the basis for their effective compensation through the tool path in real time.

For efficient machining, besides the minimization and compensation of static/geometric and thermal errors, it is vital to prevent chatter by forecasting vibrations through holistic modelling. So far, considerable advances have been made in the modelling and virtualization of the cutting process [4]. But the models still do not contain a machine tool model sufficiently accurate as regards the influence of thermal phenomena on dynamics. Therefore the integration of all the models (Fig. 4) [5] is a challenge for the improvement of vibration modelling in which also the workpiece and its thermal and dynamic properties play an important role.

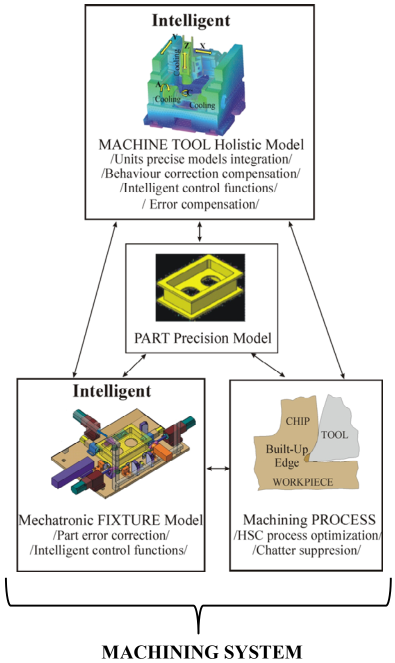

Fig. 4. Holistic model of machining system [5]

From the machining efficiency and accuracy point of view it is essential to be able to actively extend the area of chatter-free cutting conditions, i.e. to shift the stability lobe towards the higher rotational speed of the spindle. Such measures based on modelling are shown in Figure 5 [6]. The model is aided with the monitoring of the actual instantaneous state of the machining process. The solver computes the vibrations and taking into account the threshold values determines the stability lobe. It also searches for an area most advantageous for the highest possible rotational and feed speeds, taking into account the tool path data.

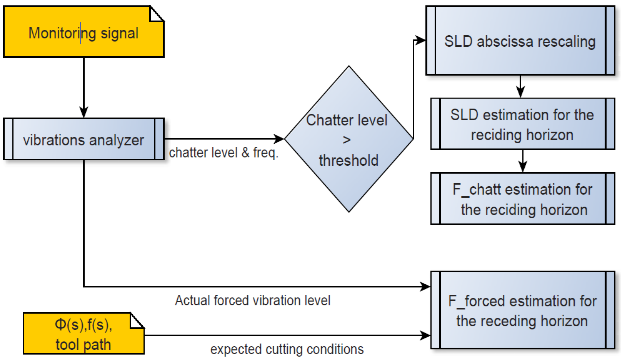

Fig. 5. In-line vibration prediction schema [6]

For control process modelling, which in tool path generation integrates CAD, CAM, CNC systems and MT data within the machining module, it is necessary to inter-connect the module components through an appropriate standard comprising a data model, CAD definitions, CAM and NC control, process planning, inspection, data packaging and an object data model. Such a standard is (Standard for the Exchange of Product model data). The standard is subject to continuous improvement. Its role in process control in real time without a postprocessor is shown in Figure 6 [7]. STEP-NC is capable of analysis and inference regarding the components and modules of the machining system.

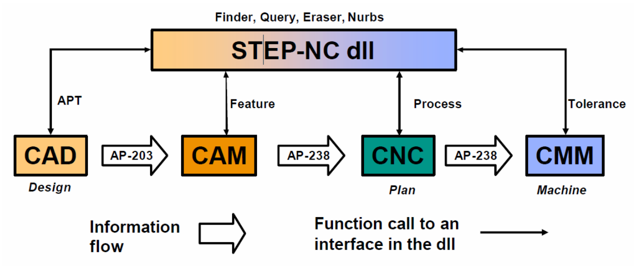

Fig. 6. Functionality of the STEP-NC DLL [7]

Appropriate interfaces ensure data transfer between STEP-NC and the particular modules [8]. Other interfaces handle data transfer between the modules. STP-NC also enables the general programming of a complex object-oriented process, as shown in Figure 7 [8].

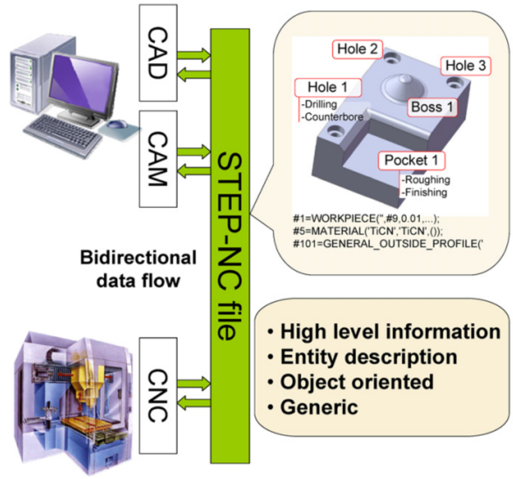

Fig. 7. New STEP-NC high level programming [8]

STEP-NC is widely used in both design (since it can describe the complexity of the part) and adaptive control (directly interconnecting process monitoring data with tool path planning in real time). It can also integrate multi-machine tool systems [8]. Moreover, STEP-NC plays an important role in the planning of a collisionless tool path. According to its development vision, STEP-NC is to have a multi-agent architecture [9]. Using STEP-NC one can accurately model complex CNC systems and integrate them with the machine tool in order to accurately take into account disturbances in the operation accuracy of the two modules in a holistic way, including speed and positioning feedbacks.

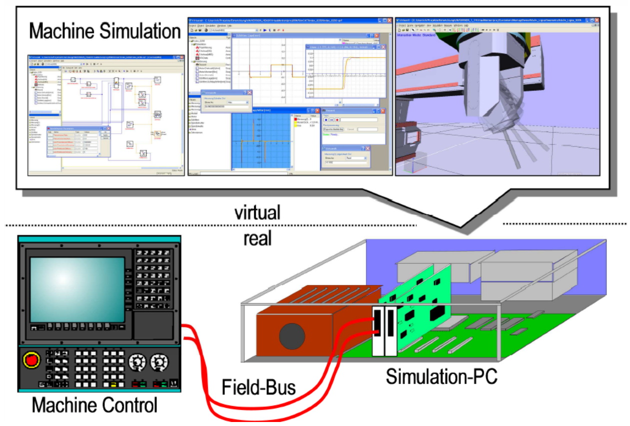

Fig. 8. Hardware in loop simulation of machine control [10]

The integrated modelling and numerical simulation of the control system and the machine tool for the set machining parameters is used to ensure good agreement between the numerically simulated dynamic lobes and the real ones. The system used for such simulation is HLS (Hardware in the Loop Simulation) which integrates the real control system and a virtual machine tool (Fig. 8) [10].

Simulation carried out in advance can provide a forecast of the dynamic behaviour of the process and enable control improvement. Quoting after [10], simulation is proper for:

- the virtual set-up of control software and hardware;
- testing control functions and the human machine interface;
- training the machine operators to eliminate irregularities efficiently;
- the optimization of control programs and machine cycle times.

Simulation should be run in real time in order to realize intelligent functions.

Stuttgart University (jointly with a software firm) has developed system VIRTUOS for HSL, which operates synchronously with the control cycle. The system has been already applied in practice. Various models are introduced through the MATLAB/SIMULINK interface. The control system must have an appropriately high processing capacity in order for the HSL to be implemented. The more complex the machine tool and process dynamics, the more accurate the model must be, which constitutes a major challenge for future research. Moreover, higher modelling accuracy results in lower process measurement (monitoring) requirements.

The integrated simulation (virtualization) of the machine tool, the control system, tool path generation, the machining process and the part in the loop greatly facilitates the machining process. This is particularly apparent in the case of complicated objects, such as aeroplane parts, when as much as 98% of the material needs to be removed through cutting and when no defective parts are permitted because of their high cost.

6. Intelligent MT concepts

Machine tool intelligent functions cover many areas, particularly tool path generation in both machining process realization (including error correction and compensation) and collision and chatter prevention. The decision taking functions pertaining to self-healing, self-control and failure prevention are more advanced because they require the realization of complex processes aided (via software) with appropriate procedures and standards (interfaces and communication).

At the present stage in the development of intelligent functions attention focuses on tool path planning and realization in real time. Since the tool path is realized through an interpolator, the latter imposes a natural time limitation. The resolution of exact interpolation is in the order of 2 nm, owing to which the outline of the workpiece can be very precisely shaped, but this can be achieved only when the tool path is realized in real time. Approximate interpolation ensures the smallest interpolation length of 2 μm reachable in 0.001 s, which can be achieved at, e.g., a feed rate of up to 12 μm, i.e. in a range of speeds much lower than the ones generally used in HSC. In the case of approximate interpolation, real time can be approached by introducing corrections at the end of the interpolation segment for the currently achievable (in control systems) time constant.

In principle, intelligent functions need to be realized in real time. In the case of an intelligent machining process, the movement of the tool shaping a part will be the result of tool path planning and realization based on a virtual digital model of the part, virtual CAM data, a virtual CNC model and a virtual machine tool model, taking into account the feedback from the instantaneous model of the machine tool representing its actual properties and those of the process and the controller through in-process measurements and positioning and dynamic feedback. In such a case, process control has an adaptive character.

The functions performed by the particular modules (from CAM to the commands passed to the executing modules of a real machine tool) are integrated by STEP-NC. In this case, STEP enables the multiaxial (multi-directional) and multi-machine tool exchange of data. Each of the controllers calculates the most advantageous process parameters, taking into account the real/simulated cutting forces. This concept is shown in Figure 9 [8]. The SPAIM platform is an advanced programming environment intended not only for milling.

The Gentelligent Components concept for machine tools, developed by the Hannover Centre for Production Technology at Leibniz University [11, 12], is highly promising. The concept consists in creating sensitive components which by means of the microsensors and microsensor data processing systems incorporated in them determine the state of the functional properties of the components and are able to pass this information to the system which can collect, analyse and then use the data to supervise, create and effect the development of components and whole products (machine tools) during their life cycle.

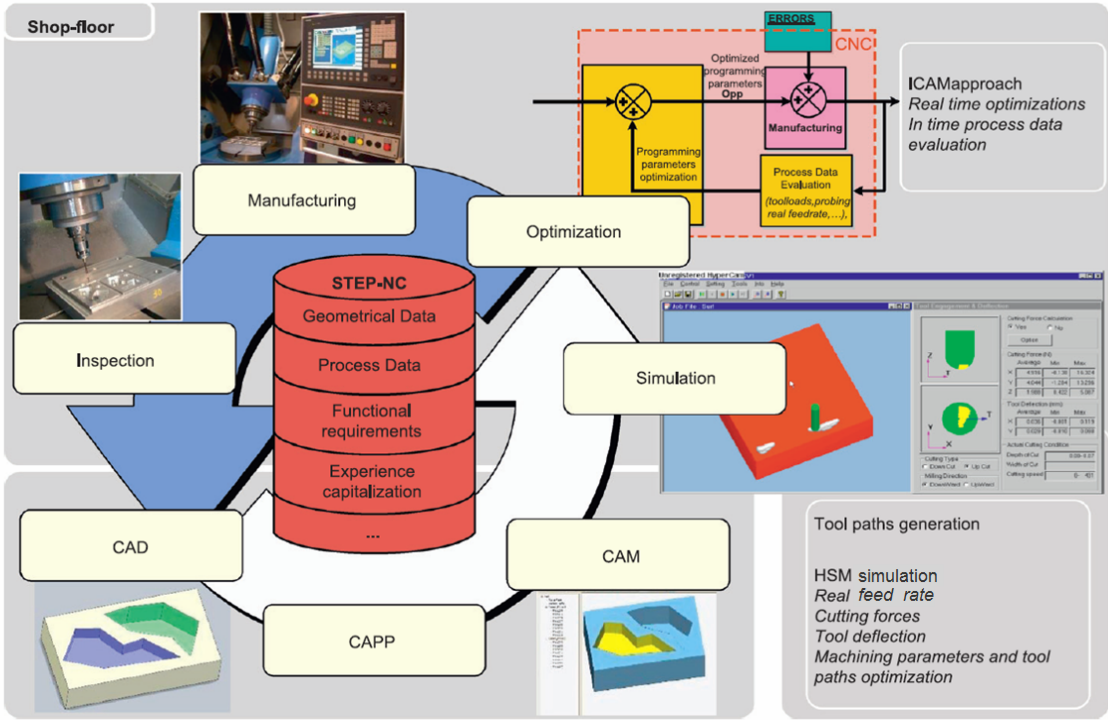

Fig. 9. SPAIM advanced numerical chain [8]

This is a concept of the holistic monitoring of machine tool elements and assemblies. The main intention of the authors [13] was to follow the state of a component from machining (Fig. 10) through operation in the whole life cycle. The intention was to use such components as modules of a system monitoring, e.g., forces and vibrations, and also in the creation of an intelligent product.

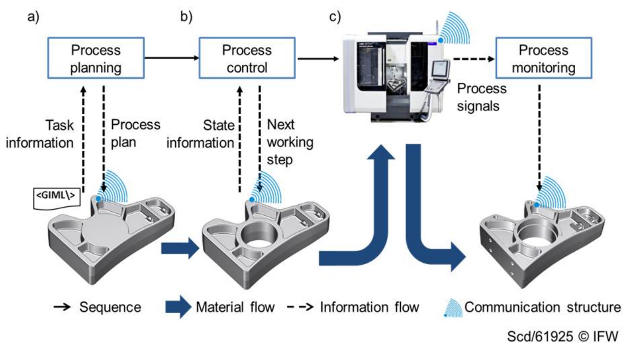

Fig. 10. Planning and control of gentelligent production [13]

This fits into the concept of the intelligent machine tool in which gentelligent components enable the intelligent recognition and shaping of its operational properties in accordance with the needs. This vision, combining holistic monitoring with actuators capable of influencing the static, thermal and dynamic properties of the particular components of the machine tool structure, creates the possibility for the holistic control of the machine tool operational properties and the machining process. In order to implement this concept many difficult problems, especially ones relating to hardware, must be solved.

The distinguishing feature of an intelligent machine tool concept today should be its realizability under all the currently existing limitations. Such a concept was developed by K. Shirase [14] from Kobe University at which many research projects aimed at the creation of intelligent machine tools [15] and whole machining systems [16] have been launched.

Shirase's concept consists in combining a digital (3D CAD) model of the part and the flexible digital modelling of computer-aided process planning (CAPP), coupled with a database. It requires process prediction and simulation coupled with process monitoring in real time, and a tool path generation strategy, taking into account the required cutting conditions and the real machine tool. The simulation of the planning process in real time turned out to be very difficult and special software had to be developed by Toyota for this purpose. The concept, referred to as

Autonomous Intelligent Machine Tool, is presented in Figure 11 [14].

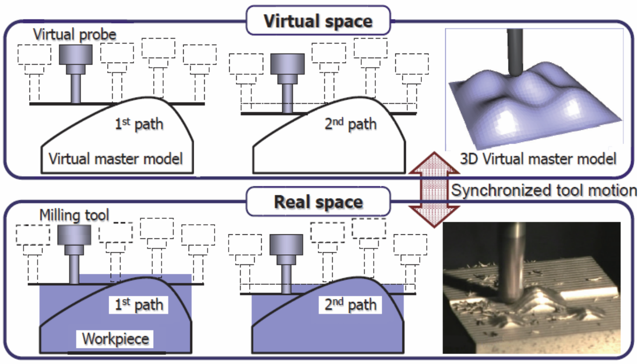

Fig. 11. Real-time tool path generation in Digital Copy Milling [14]

Copy milling, characterized by relatively low machining process speeds, was chosen to meet the real time requirements under this concept. The concept of tool path generation in real time (using digital model coupled with a real model) is shown in Figure 11. The milling of the workpiece outline and the cutting force were simulated. The digital model of the cutting force had been experimentally validated.

Shirase's concept of tool path generation [17] did not cover a detailed CNC and machine tool model, which undoubtedly significantly increased real time achievability, shifting the focus onto the adaptive control model. The possibility of detecting errors in the cutting load and preventing tool breakage was ensured.

7. Conclusions

The achievability of the holistic modelling, numerical simulation and virtualization of the thermal and dynamic behaviour of machine tools in their operating conditions and real time achievability are major determinants of the development of intelligent machine tools. The development of machine tool intelligent functions requires the digital modelling of their properties and the tool path generating components as well as the development of intelligent decision taking based on models and the real-time monitoring of the process and the adaptive control of the latter. Research should particularly focus on the creation of tool path generation models in conjunction with the development of control systems open to process generation in real time not only at low, but also at high machine tool and process dynamics. As a result, increasingly greater autonomy of the intelligent machine tool will be achieved.

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