Mechanism and Machine Theory 44 (2009) 466–476

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Beyond intelligent manufacturing: A new generation of flexible intelligent NC machines

S. Mekid [a,*], P. Pruschek [b], J. Hernandez [c]

[a] The University of Manchester, School of Mechanical, Aerospace and Civil Engineering, Manchester M60 1QD, UK
[b] Institute for Control Engineering of Machine Tools and Manufacturing Units, University of Stuttgart, Germany
[c] IDEKO Technological Centre, Arriaga Kalea, 2 20870 Elgoibar – Gipuzkoa, Spain

ARTICLE INFO

Article history:
Received 30 November 2006
Received in revised form 3 March 2008
Accepted 4 March 2008
Available online 29 April 2008

ABSTRACT

New challenges for intelligent reconfigurable manufacturing systems are on the agenda for the next generation of machine tool centres. Zero defect workpieces and just-in-time production are some of the objectives to be reached for better quality and high performance production. Sustainability requires a holistic approach to cover not only flexible intelligent manufacture but also product and services activities. New routes philosophy of possible machine architecture with characteristics such as hybrid processes with in-process inspection and self-healing will be presented with great features as well as challenges related to various aspects of the next generation of intelligent machine tool centres.

1. Introduction

Complex component machined with zero defects is a top performance in mass production and it becomes a new challenge required for the new generation of intelligent machine-tools. Increasing the precision and accuracy of machines, products and processes offers substantial benefits to a wide range of applications from ultra-precision to mass production with higher quality and better reliability. The recent development of ultra precision machines is reaching nanometre precision under very tight conditions [1,2].

The machine-tool industry is responding to a number of requirements, e.g. e_commerce, just-in-time-production and most importantly zero defect component. This is facilitated by integrating new materials, design concepts, and control mechanisms which enable machine tools operating at high-speed with accuracies below than 5 μm. However the integration of human experience in manufacturing towards flexible and self-optimising machines is widely missing. This can be achieved by enhancing existing computing technologies and integrating them with human knowledge of design, automation, machining and servicing into e-manufacturing.

The next generation will be described as new intelligent reconfigurable manufacturing systems which realises a dynamic fusion of human and machine intelligence, manufacturing knowledge and state-of-the-art design techniques. This may lead to low-cost self-optimising integrated machines. It will encompass fault-tolerant advanced predictive maintenance facilities for producing high-quality error-free workpieces using conventional and advanced manufacturing processes.

Machining process monitoring and control is a core concept on which to build up the new generation of flexible self-optimising intelligent NC machines. In-process measurement and processing of the information provided by dedicated sensors installed in the machine, enables autonomous decision making based on the on-line diagnosis of the correct machine, workpiece, tool and machining process condition, leading to an increased machine reliability towards zero defects, together with higher productivity and efficiency. Indeed, the main sensing and processing techniques in the literature [3–5] focus on

* Corresponding author. Tel.: +44 161 2003804.
E-mail address: s.mekid@manchester.ac.uk (S. Mekid).

0094-114X/$ - see front matter
doi:10.1016/j.mechmachtheory.2008.03.006

monitoring strategies for part condition monitoring (surface roughness, surface integrity and dimensional accuracy), tool condition monitoring (the so-called TCM for wear and breakage detection), process condition monitoring (chatter onset and collision detection) and machine component condition monitoring for predictive maintenance purposes (rotary components and parts subject to friction such as guideways). Since direct and in-process measurement is not generally possible due to the aggressive environment in the cutting zone surroundings, the main research effort over the last decades for part and tool monitoring has been focused on indirect measurement techniques (process condition-based), in which cutting process characteristics (i.e. cutting forces and power, vibrations, cutting temperature, acoustic emission, etc.) are measured in order to indirectly infer the part and tool condition [6,7]. Sensitivity offered by CNC internal servo signals from open architecture controllers is under study as well [8,9], since they enable the development of monitoring and control strategies without the need of installing additional sensors in the machine.

In the same way, based on the data provided by in-process monitoring, autonomous self-optimisation can be performed with the integration of process control strategies into the machine tool control architecture. Machining process control strategies are classified into two main groups [5], namely adaptive control constraint (ACC) and adaptive control optimisation (ACO).

In the former ACC control strategies, a process variable (i.e. cutting force) is kept constant and under control through the real-time in-process regulation of a cutting process parameter (i.e. cutting feed), with the aim of increasing process productivity and repeatability. Main research efforts on ACC strategies focus on cutting force control [10–12] and chatter vibration suppression [13,14].

On the other hand, special attention has to be paid to the latter process control strategies (ACO). Characteristic examples can be found at [15–19]. The main functionality provided by such control systems is the post-process self-optimisation of process parameter set-up (i.e. feeds, depths of cut, etc.), with the objective of set-up time minimisation, process knowledge management and process optimisation, towards flexible just-in-time production. With the in-process monitoring of process performance and the post-process measurement of the resulting part quality, a knowledge based process model is used to determine the new optimised set of cutting parameters, enabling autonomous self-optimisation. In the same way, as a previous step to optimisation, ACO systems are also applied to select the first process set-up for new part quality and process requirements. Therefore, if a flexible intelligent NC machine tool is to be developed, process knowledge based models are a component of primary importance to be integrated under the machine tool control architecture.

In addition to the adaptation of control parameters according to process conditions, control parameters have also to be optimal during handling (including changing operations of work pieces and tools) and positioning operations as these operations account typically for more than 50% of the overall operating time. Earlier methods for parameter optimisation concentrated on the reduction of positioning and settling times of the feed axis by tuning only a few basic control parameters (e.g. gain of the position control loop and gain and reset time of the velocity control loop). With increased computational power, optimisation methods as described in [20] can now be reinvestigated for the use with a wider parameter set including the parameters for acceleration and jerk limits which are directly influencing the vibrations of an axis.

If the characteristics of a controlled axis are known by means of the vibration behaviour, an adequate generation of the programmed trajectories can yield a further optimisation. Methods for input shaping [49] can be used to design trajectories that do not excite resonant frequencies of a given system. Hence, settling times and thus positioning times can be further reduced.

Concerning parameter optimisation through self-learning particularly, the interest of the so-called machine learning approaches [21] will be introduced as the main research trend in process monitoring and control strategies towards the intelligent manufacturing system.

2. Expected characteristics of the next generation

The expected characteristics of the next generation of machine centres are described as follows:

(a) *Integration:* development of an integrated machine tool being capable of performing both conventional and non-conventional processes in one platform. (b) *Bi-directional data flow:* definition of a bi-directional process chain for unified data communication exchange between CAD, CAM, CNC and Drive systems. (c) *Process control loop:* development and CNC integration of robust and reliable real-time strategies for the in-process tool, part, and process condition monitoring and control. (d) *Predictive maintenance:* specification of a load- and situation-dependent condition monitoring for machine components as a basis for self-reliant machine operation. This will be followed by the formulation of a self-organising predictive maintenance schedule that is based on self- and remote diagnostics and covers both short and long term aspects. (e) *Autonomous optimisation:* development of a self-configuring self-optimising control system for autonomous manufacturing, based on the in-process monitoring, characterisation and management of process knowledge. To facilitate such characteristics, the following topics will be necessary to be implemented:

(a) To develop an integrated intelligent machine centre dedicated to e-manufacturing.
(b) To investigate and develop fast, stable and stiff reconfigurable machines with hybrid machining processes to prepare a new platform for future machine-tools.
(c) To investigate implementation of total error compensation and in situ inspection facility.

(d) To develop and produce new methodologies and concepts of autonomous manufacturing, self-supervision and self-diagnostic/tuning/healing.
(e) To develop and integrate real-time process controllers into open CNC and drive system architecture, taking the machine from an axis-controlled system to a machining process-controlled self-reliant system, based on the on-line information provided by robust and reliable sensing techniques for tool, part, and machining process condition monitoring.
(f) To develop and incorporate an extendible and knowledge based CAM system capable of recognising complex features, performing self-learning based on in-process monitored data provided by machine control loops, and autonomously determining the optimum tools/sets for given requirements of part quality, machine productivity and process efficiency. Following the e-manufacturing approach, in a second step, CAM systems capable of sharing self-optimised process knowledge between networked machines are to be developed.

An interdisciplinary approach of machine-tool builders in order to achieve these objectives becomes necessary and includes control manufacturers, research institutions and potential end-users. Such a development will realise a number of breakthroughs in the future, e.g. (a) *Delay-free cum zero-downtime production:* the proposed e-manufacturing approach will see the use of electronic services based on available data from machined processes, sensor signals, and human experience that is integrated in a zero delay-time system to enable machines with near zero-downtime and production that meets user requirements with zero delay time. (b) *Self-reliant production:* machines will be enabled to operate widely autonomously. (c) *Optimal production:* self-configuration and self-optimisation will eliminate production errors down to the limitations of the in-process measurement devices.

3. Concepts of intelligent and flexible machines

In Fig. 2, the authors propose a new integrated concept for the next generation of machine tool centres. Based on the knowledge acquired and the features extracted, the performance of control systems will be extended towards self-controlled manufacturing with the objectives of cost-effective, high quality, fault-tolerant and more flexible systems with better process capability. New intelligent control systems have to be developed and integrated with open architecture controllers such as OpenCNC® or OSACA-based CNCs. In order to allow an automated error-free production with near zero down time, open interfaces, learning capabilities, self-tuning and self-adjusting mechanisms as well as sophisticated model-based prediction instruments have to be implemented at these layers. Quality inspection could operate in situ with environmental conditions taken into account. For the first time, the concept of self-healing with e-maintenance could be operational.

3.1. Industrial requirements for machining process monitoring and control

Among the future requirements that have to be focused on, are the aspects of the just-in-time-production and zero defect components, together with continuously higher part quality and process productivity. Automation level provided by machining process monitoring and control systems contributes to those requirements. However, taking into account that there is a growing need for production of small lot sizes in the market, flexibility lack in such automation systems is the main drawback to deal with.

Indeed, flexible monitoring systems are required under the actual market requirements and thus, reliable process diagnosis is necessary under different cutting conditions. Nowadays, a common problematic shared by conventional process monitoring approaches for part and tool condition monitoring is the lack of reliability under changing cutting conditions hence limiting the flexibility of such automation systems [3]. As a characteristic example of this problematic for process condition based tool condition monitoring (TCM), the process condition is not only influenced by changes in tool condition, but it is also directly affected by cutting conditions. Furthermore, under different cutting conditions, different wear mechanisms can be activated on the tool, each one having its particular impact on process and part condition. Therefore, when setting-up process monitoring systems for new cutting conditions, previous trials for process signal database retrieval are required [4]. These are combined together with skilled operators with the necessary process knowledge in order to interpret changes in process behaviour (i.e. forces, vibrations, etc.) and set-up suited detection limits. Additionally, flexible process monitoring equipments often requires additional sensors that can fail and result in unforeseen downtime. As a result, when high flexibility is required, monitoring systems are usually switched-off in industry, and direct post-process measurement is performed, with the corresponding reliability lack in the machined part quality.

Dealing with such a problematic, model-based process monitoring and sensor fusion approaches are pointed out as the alternative in order to get reliable process condition diagnosis, with a clear research effort over last years for machining processes such as turning [22–24], grinding [4,25,26] and milling [27].

On the other hand, the integration of human experience in manufacturing is widely missing concerning machining process optimisation. Set-up time reduction is critical when flexible just-in-time production is required. Nowadays, set-up-time mainly depends on process knowledge concentrated in skilled operators, and there is a lack of systematic management, retrieval, sharing and optimisation of that key knowledge. Furthermore, characterisation of process knowledge and development of models for autonomous process optimisation are required if set-up times are to be drastically reduced.

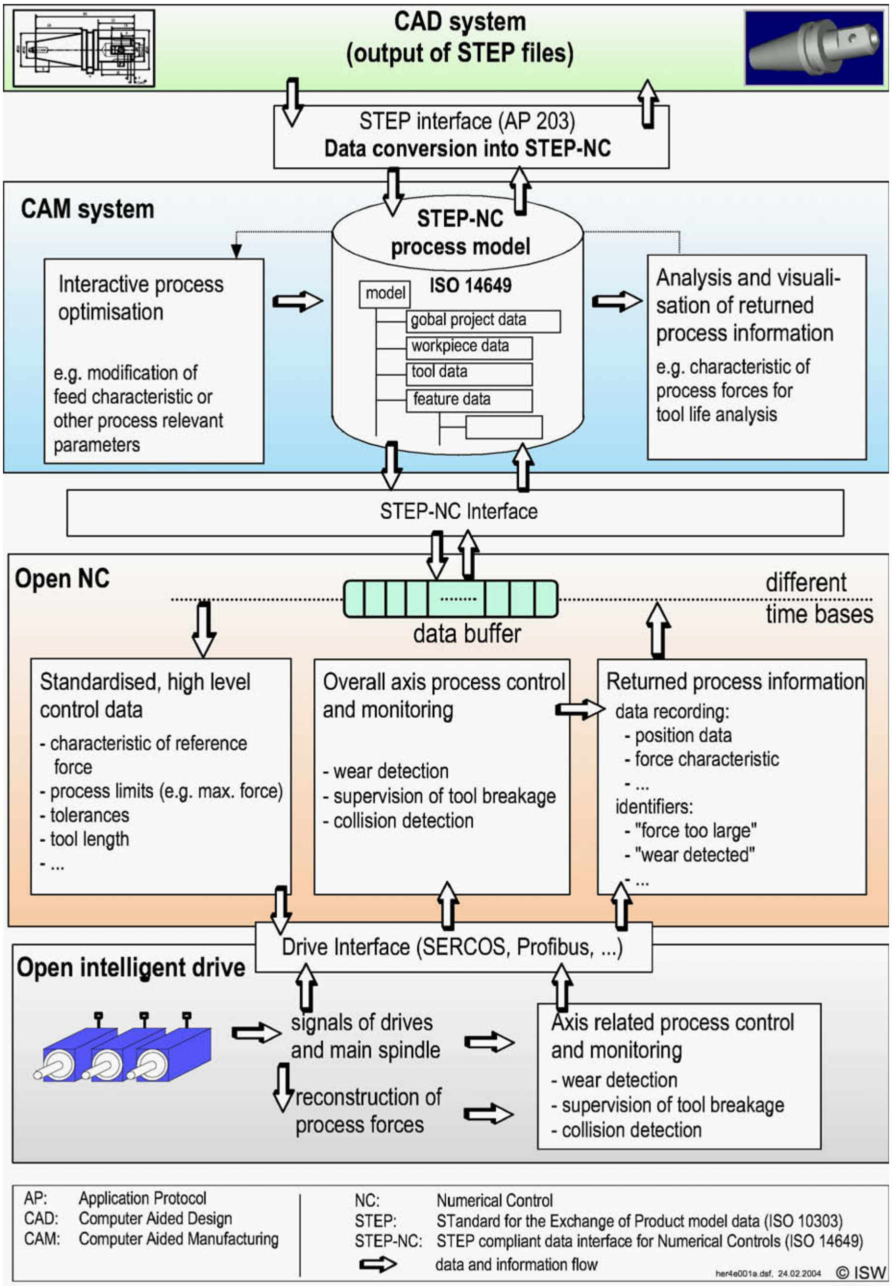

Fig. 1. Bi-directional process chain.

Concerning this process knowledge related problematic, intelligent manufacturing systems (IMS) are the key on going research concepts. The main objective of the IMS concepts is the development of an autonomous machine tool control system able to perform self-tuning and self-learning, provided by the on-line monitoring and retrieval of cutting process related knowledge (i.e. forces, part quality, machining time, tool life econometrics, predictive maintenance, etc.), towards flexible and self-optimising machine tools. With the successful incorporation of IMSs into machine tool control integrated CAM systems, set-up times for new parts and process optimisation needs will be minimised, enabling just-in-time production, independent from machine operator skills.

3.2. New possibilities in knowledge based society

The core concept of developing a flexible machine operated by a controller that performs process-adaptation on the basis of a bi-directional data exchange between all parts of the process chain will yield a completely new way of manufacturing,

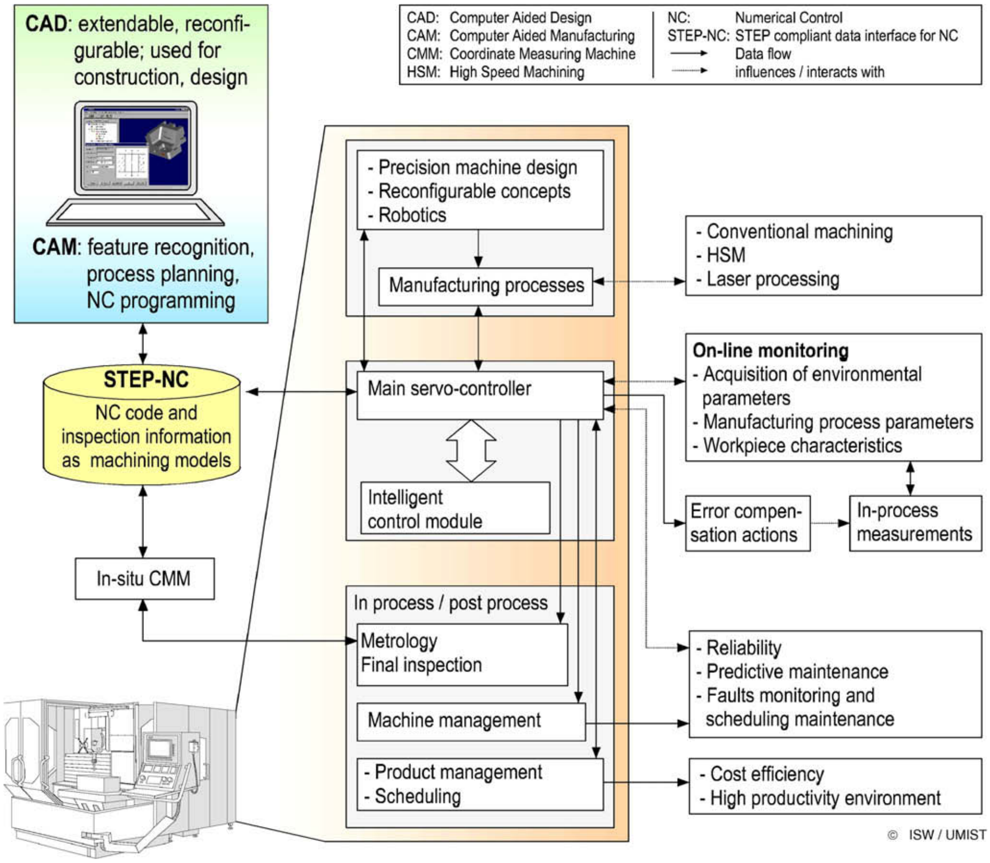

Fig. 2. A new approach for the future machine centres.

especially small lot sizes, (Fig. 1). Economically speaking, this will have a large impact on end-users of machine tools that will be able to meet customer requests in shorter time.

In addition to adaptiveness, there is a growing need for intelligence in numerical controllers as processes are becoming more complex and manufacturing time has to be decreased. Much of this intelligence can be realised by introducing e-technologies for self-maintenance supported by remote-maintenance functions. If a machine has the ability to be serviced in part preparation, load-dependent monitoring, fault diagnosis from internal and external knowledge bases, optimal manufacturing can be guaranteed while downtimes and set-up times are minimised, especially when a variety of different parts must be manufactured in a short time.

Consequently, the most important advantage for end-user will be the availability of machines that are able to operate in a self-reliant manner, self-optimising and automatically serviced. Thus, there is no need to employ a number of cost-expensive personnel to accomplish a large number of different process types which is not profitable to small companies.

At first glance, the advantages for machine tool builders may be less obvious. By taking a closer look, it is obvious that with a growing need for production of small lot sizes there is also a growing market for machine tools to fill this gap. Although a number of approaches to build modular machines and controls are known, their application to commercial products is missing as these approaches are mostly scientific.

Concepts could be created to combine modular machine approaches with modular numerical controllers that integrate e-technologies derived from other disciplines, namely e-business and e-servicing. By generating common knowledge bases of machine abilities and possible machine disabilities and faults, not only an automated maintenance can be achieved but also an automated machine design optimisation which mainly addresses the machine tool builders, towards a holistic product life cycle management (Fig. 3).

3.3. Research trends in process monitoring and control towards IMSs

The expertise in the machine-tool sector must rapidly converge towards new paradigms of production and new concepts of product-services and will move to a production industry from resource-based towards knowledge-based approaches, to remotely manufacture on-demand, multi-use, upgradeable product-services. Intelligent manufacturing systems (IMSs) are a

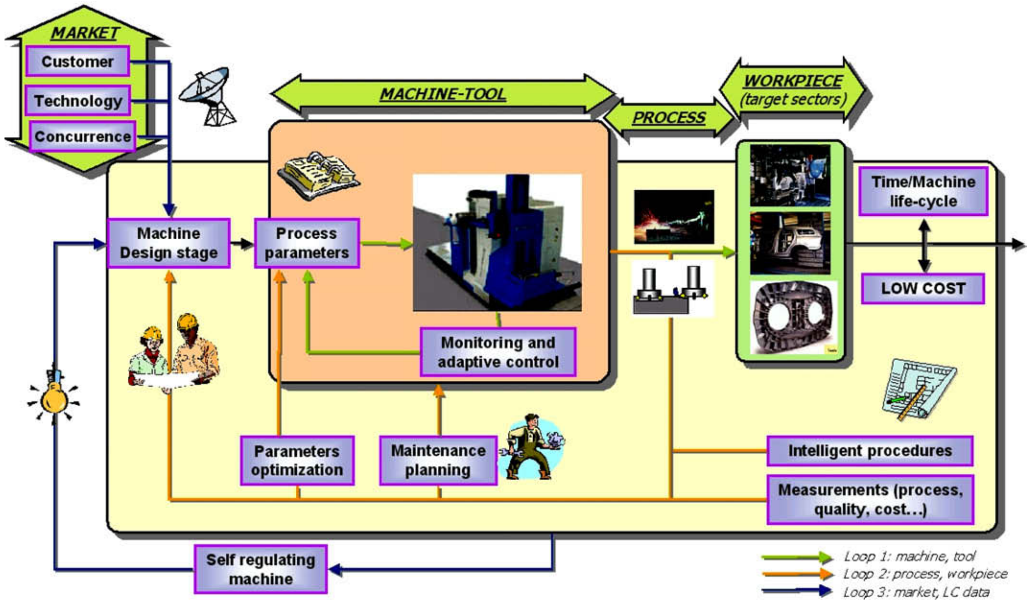

Fig. 3. Holistic approach to evolutionary manufacturing.

research area with world-wide interest encompassing all industrialised nations. Progress has already been made in countries such as the USA, Japan, Canada and Australia; European countries have also initiated some work in this area. In order to make a significant impact, the next generation of IMS should embody not only the processes but also the associated 'intelligence', so that they can be used to manufacture high-value components with near-zero faults.

Integration of human expertise into machine tool control system has been a key research issue over last years in the machining process monitoring and control field. It can be emphasised that intelligence is strongly connected with learning. Learning ability must be an indispensable feature of future IMSs. In particular, artificial intelligence (AI) modelling approaches under the machine learning concept (knowledge-based systems (KBS), expert systems (ES), artificial neural networks (ANN), fuzzy logic (FL), etc.) have to be pointed out as a core concept for the new generation of intelligent NC machines. A comprehensive study in machine learning approaches for machining process monitoring and control can be found at [21].

On the other hand, regarding the integration of monitoring and control systems into machine control architecture, most of the control strategies are single input single output (SISO), as in ACC strategies for force control, where only one process variable in controlled (i.e. cutting force) through the regulation of one process parameter (i.e. feed). However, in order to deal with the existing interdependence between different process variables, first proposals in the literature consider MIMO approaches (multiple input multiple output) [28], where multiple inter-related controlled variables and regulating parameters are considered. Following that integration trend, ACC strategies subordinated to ACC controllers are also presented [29].

Recently, there has been work focusing on integration of multiple controllers leading to research in supervisory control systems [11,30], where the joint processing of the data concerning machining process, part, tool and machine component conditions is carried for the co-ordinated management and situation-dependant decision making onto the corresponding set of subordinated and inter-dependant process control modules. Several approaches and techniques can be found for supervisory system development: KBSs [31,32], hierarchic control systems [33,34], Grafcet based decision-making [35], etc. An example of the superior performance of a supervisory control system over independent single controllers in terms of productivity and part quality can be found at [36]. Additionally, as a potential advantage of such an integrated approach, networked supervisory systems to machine component suppliers will enable periodical remote machine condition inspections, leading to fault-tolerant advanced predictive maintenance facilities for producing high-quality error-free workpieces.

Therefore, a systematic design approach is necessary for the effective construction and implementation of supervisory systems into an open-architecture machine tool control as inter-dependant and co-ordinated machining process control modules.

3.4. Aspects of the new generation of machine tools

The next generation of machine tools will be reconfigurable and self-adaptive as single machine or within a manufacturing system. It is designed for a rapid change in structure and components in order to rapidly introduce a new product and adjust production capacity and functionality in response to market changes.

The next generation of machines will be characterised by a limp from independent assembled sensor, actuator and controls towards mechatronic knowledge based system. The machines could also be modular with embedded intelligence and standardised interfaces to be able to assemble and reconfigure. To Secure work envelope, high dexterity, high stiffness, etc., in the new configuration knowing the programmed tasks, a rapid simulation should be computed to check specifications. The innovative design of the next generation is heading towards adaptronic modules, i.e. intelligent spindle, haptic cutting tools and real time reconfiguration interfaces.

Hence, the aspects have to be addressed for the next generation of machine tools:

- New self-adaptive machine structures based on mechatronic concepts.
- Mechatronic knowledge-based intelligent modules.
- Integrated process control with in-process product characterisation.
- Intelligent manufacturing equipment.
- Development of tools for integrated/embedded optimised system.
- Embedded simulation capability for current configuration.
- Scalability of the machines.

4. Virtual design and simulation

Virtual machine tool engineering gives the possibility to design, test, optimise, control and machine parts in a computer simulation environment. This saves much time and money in avoiding build the first test-prototype. The rigid and flexible machine tools models are analysed under various jerk, acceleration, velocity and control profiles at high speeds. The coupled simulation of machine structure, drives and CNC control offers not only the chance to study the interactions between the different instance for offline optimisations of a new machine tool. In contrast, real-time simulation models are able to be connected to a real CNC building a hardware-in-the-loop system which allows for optimisation of control parameters and a completely virtual ramp-up process [37].

The digital model of the machine is integrated to the numerical simulation of the cutting process; hence the machine tool can be tested to machine particular parts under desired cutting conditions. However, the virtual machine tool technology still requires fundamental research in the area of process simulation, integration of all analysis modules in a user friendly simulation programme for the users [38]. Fundamentals of precision engineering with second and third order errors could be taken into account in the design process to drastically reduce most of the errors [39].

Simulation of manufacturing processes using multi agent technologies allows testing of various configurations of production processes and locates bottlenecks and other possible problems [40]. To achieve higher accuracy in machining at micro and macro scale, full virtual simulation including control, manufacturing process and mechanical capabilities are required.

5. Intelligent open architecture controllers

Successful development and implementation of supervisory systems concerning process monitoring and control demands high flexibility for the machine tool controller architecture [3], both for software and hardware component integration and upgrading. Open architecture control (OAC) is a concept derived from this flexibility requirement. In particular, PC-based homogeneous and standardised platforms are pointed out as the best solution for flexibility [41]. Although there are available commercial solution in the market under the OAC concept (Delta Tau PMAC-NC, IBH PA 8000, etc.), together with large international consortiums addressing this field (OSACA in Europe, OMAC in United States, JOP in Japan, etc.), the use of OAC systems is still limited to research and development activities, since standardisation still remains unresolved for their widespread application in the machine tool industry.

Nowadays, most of the available commercial process monitoring and control systems (Prometec, Artis, etc.) remain as add-on external hardware systems integrated to machine tool CNCs, with various available communication standards (Ethernet, Profibus, CAN, etc.), and with a clear trend towards higher HMI (Human Machine Interface) integration level as additional and flexible software modules into PC-based CNCs. There are only few systems that allow the integration of process monitoring routines at a lower level. An example for an open system is the newest generation of servo-drives offered by Bosch-Rexroth which has a freely programmable PLC. Bosch-Rexroth's own productivity agent is using this PLC to offer monitoring and maintenance algorithms based on drive signals (current and scale information). However, processing algorithms and decision making strategies integrated by commercial systems are relatively simple, and the ability to extend system resources in order to upgrade system performance through the integration of process knowledge in terms of complex user-defined signal processing algorithms and advanced control strategies is widely missing. Furthermore, standardised interfaces are missing that enable the distribution of monitoring, control and servicing algorithms to different NC and drive platforms at the levels of velocity and current control (i.e. below 1 ms cycle times). On the other hand, last generation of open CNCs available in the market (Fanuc, Siemens, etc.) offer the possibility of real-time execution of user-defined control algorithms in the cycle times of the position controller (usually $\geqslant 1$ ms). Again, programming languages for such algorithms are

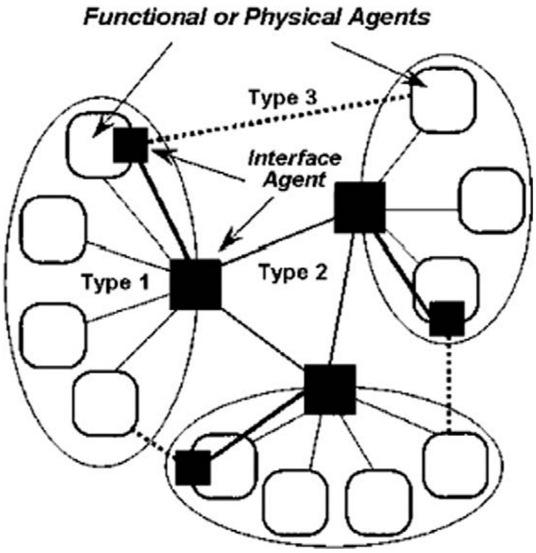

Fig. 4. Hybrid network application.

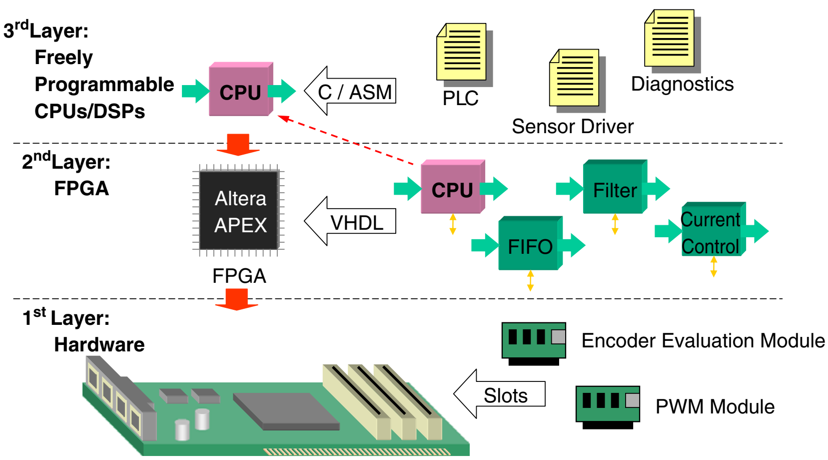

Fig. 5. Open drive architecture.

proprietary solutions, with a clear lack of a standard in this field. In the same way, complexity of programmable algorithms is still restricted by the limited processing capability offered nowadays.

A core problem that hinders the realisation of flexible interfaces is related to the system design. Both drives and CNC are usually based on digital signal processors or microcontrollers. Both types of processing units feature a serial execution of all tasks. Consequently, a complex task scheduler must be implemented to guarantee a stable real-time processing of data. Control, monitoring and serving tasks can never be performed in a truly parallel way. An alternative to these serial control systems are units that are based on field programmable gate arrays (FPGA). With new FPGA-based control platforms, it is possible to configure drive controllers and PLCs on one chip using hardware description languages (VHDL). All of these units can access the same signals and process data in parallel in hard real-time. As an extension to the set of control and PLC functionality, it is possible to instantiate complete DSPs or CPUs as additional units. As these blocks are not simulated but established as real hardware circuits, they can execute sophisticated code that is programmed in high level languages (C, Assembler) in the same way as the low-level units – in real-time and in parallel. A sketch of an open drive architecture is shown in Fig. 5 [50].

6. Concept of self-healing in machines

Self-healing is an important feature required in the new generation of machine-tools. This will go beyond faults monitoring and scheduling maintenance to achieve extremely high reliability. The aim is to heal a component from software and environmental errors. A worst case would be to replace a defect component by either automatic maintenance scheduling, or, engage a new mode of functioning among others in the machine but this would need prediction of scenarios at the initial stage of the machine design. Once this is possible, it is assumed that the system would never fail, hence and great increase in life time and economic outcomes.

The concept of self-healing in software based systems will intervene after perceiving faults and attempt to solving bugs and conflicts, make the necessary adjustments and restore a working order required for the particular on-going application. Human intervention could be required; otherwise agents could be programmed to assist the self-healing. While writing this paper an interesting survey has been published to cover self-healing software based systems [42].

Many active research developments are working in this direction and could support machine design aspects like new materials such as composite materials that can heal themselves. Fibres break under relatively low impact loads releasing repair agents that seep into the cracks and harden, repairing the damage [43]. Nervous materials could also be key materials for machines as the can feel ‘pain’ and attempt to recover from it, hence bringing the machine dynamic and thermal characteristics back to requirements.

7. Up-coming intelligent multi or hybrid agent systems

Recent agents have been developed to address a number of obstacles and ease the use both communication and parameter monitoring in manufacturing. Sensor clustering becomes a very attractive application particularly in manufacturing where various types of phenomena are monitored and information should be exchanged between internal sensors (i.e. drive sensors to measure current and positions), external sensors (such as vibration sensors) and the CNC control that supervises the machine performance.

It is clear that agents have to either work alone or cooperate to achieve a task. The question could be whether a single agent could perform all the tasks or the concept of multi-agent has to be introduced. Communication between agents is important to transfer information between agents with a capability of prioritization. With multi-agent systems could parallel computation be used to speed up the system. Robustness, scalability and the programming become easier [44].

Multi agent systems would not probably be of systematic use if the system is not suitable or if it is applied it may introduce delays or will be an expensive solution. Further multi-agents are not suitable when used only to decentralise a system normally modelled as a centralised system. One should not try to provide multi-agent solutions to the non-suitable problems, it is foremost important to focus on the problems the multi-agents are meant to solve and not on the possible benefits [45].

Today the focus of agent research is more on multi-agent systems than on single agent systems, since agents that co-operate and/or communicate can solve much more complex tasks than just one single agent is capable of [46]. Verification and validation of multi agents has already been addressed in [47]. Learning and autonomous capabilities should be part of the multi-agents strategy. Nahm and Ishikawa [48] have proposed a hybrid network of agents as shown in Fig. 4, they employ a lightweight middle agent, called “interface agent” for continuous or discrete interactions between local agents (type 1), between a collection of local agents and a collection of remote agents (type 2), and between a local agent and a remote agent (type 3). Therefore, agent interactions are made only via the interface agent.

Concerning networked machines to a central process knowledge server, process information data can be forwarded to a centralised agent for expert analysis and decision making [3], sharing knowledge to thirds in the net. Synergistic union of networked machines could perform as process knowledge generation nodes.

8. Concluding remarks

Although strong research efforts have been conducted over the last decades in machining process monitoring and control field, there has been little transfer of such technologies into industry. The main lacks to overcome the challenges in order to increase the impact and to bring all the potential benefits provided by such automation and optimisation systems into machine tool industry could be summarised as follows:

(a) Development of robust sensing and signal processing techniques, implementing monitoring and control techniques proposed in the literature into usage requirements of real life applications (e.g. aggressive environment, fluids, noise and chips), both for direct and indirect measurement techniques. Miniaturisation and embedding of sensors and actuators into machine tool components is an on going exciting research trend.

(b) Development of reliable and process knowledge-based diagnosis with control strategies, so that systems could be autonomously self-adapted with zero set-up time for the end user, operating under a wide range of machining conditions and part requirements. As a result, without the need of skilled operators, flexible application of process automation and optimisation systems will become possible under changing market requirements.

(c) Adoption of OAC systems including integrated and co-ordinated open process controllers, towards the industrial standardisation of machining process monitoring and control systems, enabling the integration of user-defined, flexible, self-learning and multipurpose supervisory systems.

(d) Synergistic and co-ordinated research and development efforts between machine tool builders, control manufacturers, research institutions and machine end-users, avoiding resource overlapping, and enabling high-risk and long-term studies for ground-breaking results.
(e) Development of new ‘adaptronics’ for modular machines with mechatronic aspect to ease reconfiguration of the next generation of machine tools.

Intelligent process control should address both workpiece quality (dimensional and material integrity with surface finish quality) and the related cost in terms of tooling and time. This can be best accomplished by using precise process models and sensory information in an open-architecture control environment. To achieve these objectives it is required to use precise process models with compliant cluster sensors within an open architecture control environment. In addition, it is also required to develop and integrate a variety of support technologies as mentioned previously.

References

[1] H. Mizumoto, S. Arii, Y. Kami, M.Yabuya, A single-point diamond turning machine with micro cutting mechanism using active aerostatic guideway, in: MATADOR Conference, Manchester, 2004.
[2] W. Gao, Construction and testing of a nano-machining instrument, Precision Engineering 24 (2000) 320–328.
[3] S. Liang, R. Hecker, R. Landers, Machining process monitoring and control: the state-of-the-art, Journal of Manufacturing Science and Engineering 126 (2004) 297–310.
[4] H.K. Tönshoff, T. Friemuth, J.C. Becker, Process monitoring in grinding, Annals of the CIRP 51 (2) (2002) 1–21. Keynote papers.
[5] H.K. Tönshoff, I. Inasaki, Sensors in manufacturing, Sensors Applications, vol. I, Wiley & Sons, 2001, ISBN 3-527-26538-4.
[6] S.E. Oraby, D.R. Hayhurst, Tool life determination based on the measurement of wear and tool force ratio variation, International Journal of Machine Tools and Manufacture 44 (2004) 1261–1269.
[7] J.F. Oliveira, D. Dornfeld, Application of AE contact sensing in reliable grinding monitoring, Annals of the CIRP 50 (1) (2001) 217–220.
[8] E.S. Lee, J.D. Kim, Plunge grinding characteristics using current signal of spindle motor, Journal of Materials Processing Technology 132 (2003) 58–66.
[9] G. Pristschow, J. Bretschnerider, S. Fritz, Reconstruction of process forces within digital servodrive systems, Production Engineering VI (1) (1999) 73–78.
[10] S.I. Kim, R.G. Landers, A.G. Ulsoy, Robust machining force control with process compensation, ASME Journal of Manufacturing Science and Engineering 125 (2003) 423–430.
[11] Y. Liu, T. Cheng, L. Zuo, Adaptive control constraint of machining process, International Journal of Advanced Manufacturing Technology 17 (2001) 720–726.
[12] R.L. Hecker, S.Y. Liang, Power feedback control in cylindrical grinding control, ASME International Mechanical Engineering Congress and Exhibition 69 (2) (2000) 713–718. Orlando, Florida, DSC.
[13] R.G. Landers, A.G. Ulsoy, Machining force control including static, nonlinear effects, in: Japan USA Symposium on Flexible Automation, Boston, MA, 1996, pp. 983–990.
[14] R. Radulescu, S.G. Kapoor, R.E. DeVor, An investigation of variable spindle speed face milling for tool-work structures with complex dynamics, Part 1: Simulation results and, Part 2: Physical explanation, ASME Journal of Manufacturing Science and Engineering 119 (1997) 266–280.
[15] G. Amatay, S. Malkin, Y. Koren, Adaptive control optimisation of grinding, ASME Journal of Engineering for Industry 103 (1981) 103–108.
[16] Y. Koren, The optimal locus approach with machining applications, ASME Journal of Dynamic Systems Measurement and Control 111 (1989) 260–267.
[17] W.B. Rowe, L. Yan, I. Inasaki, S. Malkin, Applications of artificial intelligence in grinding, Annals of the CIRP 43 (2) (1994) 521–531.
[18] R. Ivester, K. Danai, S. Malkin, Cycle-time reduction in machining by recursive constraint bounding, ASME Journal of Manufacturing Science and Engineering 119 (1997) 201–207.
[19] Y. Li, W.B. Rowe, X. Chen, B. Mills, Study and selection of grinding conditions: Part I: A hybrid intelligent system for selection of grinding conditions, Proceedings of the Institution of Mechanical Engineers 213 (1999) 131–142.
[20] G. Pritschow, J. Bretschneider, A self-tuning controller for digitally controlled electromechanical servo drives in machine tools, Annals of the International Institution for Production Engineering Research (1999).
[21] L. Monostori, A. Márkus, H. Van Brussel, E. Westkämpfer, Machine learning approaches to manufacturing, Annals of the CIRP 45 (2) (1996) 675–712.
[22] T. Obikawa, J. Shinozuka, Monitoring of flank wear of coated tools in high speed machining with a neural network ART2, International Journal of Machine Tools and Manufacture 44 (2004) 1311–1318.
[23] Y.M. Niu, Y.S. Wong, G.S. Hong, T.I. Liu, Multi-category classification of tool conditions using wavelet packets and ART network, Journal of Manufacturing Science and Engineering 120 (1998) 807–816.
[24] X.Q. Li, Y.S. Wong, A.Y.C. Nee, A comprehensive identification of tool failure and chatter using a parallel multi-ART2 neural network, Transaction of the ASME Journal of Manufacturing Science and Engineering 120 (1998) 433–442.
[25] Jr. J.E. Mayer, G. Purushothaman, S. Gopalakrishnan, Model of grinding thermal damage for precision gear materials, Annals of the CIRP 48 (1) (1999) 251–254.
[26] I. Inasaki, Sensor fusion for monitoring and controlling grinding processes, International Journal of Advanced Manufacturing Technology 15 (1999) 730–736.
[27] G. Pritschow, S. Fritz, P. Pruschek, Reconstruction of process forces of direct drives using the Ferraris sensor, in: International Conference on Monitoring and Automatic Supervision in Manufacturing AC 04, Zakopane, Poland, 2004.
[28] R. Ardekani, I. Yellowly, The control of multiple constrains within an open architecture machine tool controller, ASME Journal of Manufacturing Science and Enginerring 118 (1996) 388–393.
[29] T. Lundholm, A flexible real-time adaptive control system for turning, Annals of the CIRP 41 (1991) 441–444.
[30] R.G. Landers, A.G. Ulsoy, Supervisory machining control on an open-architecture platform, in: CIRP International Conference and Exhibition on Design and Production of Dies and Molds. Istanbul, Turkey, 1997, pp. 97–104.
[31] Z. Katz, T. Van Niekerk, Implementation aspects of intelligent machining, Proceedings of the Institution of Mechanical Engineers 217 (2003) 601–613.
[32] K. Ramamurthi, C.L. Hough, Intelligent real-time predictive diagnositics for cutting tools and supervisory control of machining operations, ASME Journal of Engineering for Industry 115 (1993) 268–277.
[33] A. Dasgupta, B. Pandurangan, R.G. Landers, S.N. Balakrishnan, Hierarchical optimal control of turing process-linearization approach, in: American Control Conference, Denver, Colorado, 2003, pp. 2606–2613.
[34] R. Teltz, M.A. Elbestawi, Hierarchical knowledge-based control in turning, ASME Journal of Dynamic Systems Measurement and Control 115 (1993) 268–277.
[35] R.G. Landers, A.G. Ulsoy, Supervisory machining control: design and experiments, Annals of the CIRP 47 (1) (1998) 301–306.
[36] R.G. Landers, A.G. Ulsoy, A supervisory machining control example, in: International Conference on Recent Advances in Mechatronics, Istanbul, Turkey, 1995, pp. 990–997.
[37] S. Roeck, H. Ruedele, Real-time simulation environment for machine-tools, in: 2nd International Conference on Advanced Research in Virtual and Rapid Prototyping, Leiria, Portugal, 2005.

[38] Y. Altintas, C. Brecher, M. Weck, S. Witt, Virtual machine tool 2005 Keynote Paper of STC M, Annals of CIRP 54 (2) (2005) 651–674.
[39] S. Mekid, Design strategy for precision engineering: second order phenomena, Journal Engineering Design 16 (1) (2005) 63–74.
[40] J. Vokrinek, D. Pavlicek, R. Smerak, Simulation of manufacturing processes using multi-agent technologies, in: IPROMS Virtual Conference, 2005.
[41] G. Pritschow, Y. Altintas, F. Jovane, Y. Koren, M. Mitsuishi, S. Takata, H. Van Brussel, M. Weck, K. Yamazaki, Open controller architecture – past present and future, Annals of the CIRP 50 (2001) 463–470.
[42] D. Ghosh, R. Sharman, H. Raghav Rao, S. Upadhyaya, Self-healing systems – survey and synthesis, Decision Support Synthesis 42 (2007) 2164–2185.
[43] J.M. Hoffman, Self-healing spacecraft: aerospace engineers are on the cusp of developing composites that can repair themselves, Machine Design (2006).
[44] P. Stone, M. Veloso, Multi-agent systems: a survey from a machine learning perspective, Technical Report 193, Department of Computer Science, Carnegie Mellon University, Pittsburgh, PA, 1997.
[45] T.C. Collier, C. Taylor, Self-organization in sensor networks, Journal of Parallel and Distributed Computing 64 (2004) 866–873.
[46] E. Benoit, L. Foulloy, High functionalities for intelligent sensors, application to fuzzy colour sensor, Measurement 30 (2001) 161–170.
[47] M. Bourahla, M. Benmohamed, Formal specification and verification of multi-agent systems, Electronic Notes in Theoretical Computer Science 123 (1) (2005) 5–17.
[48] Y.E. Nahm, H. Ishikawa, A hybrid multi-agent system architecture for enterprise integration using computer networks, Robotics and Computer-Integrated Manufacturing 21 (3) (2005) 217–234.
[49] M.N. Sahinkaya, Input shaping for vibration-free positioning of flexible systems, Proceedings of the Institution of Mechanical Engineers, Part I, Journal of Systems and Control Engineering 215 (I5) (2001) 467–481.
[50] G. Pritschow, C. Kramer, Open system architecture for drives, in: Proceedings of the 55th CIRP General Assembly, Antalya, Turkey, 2005.