ORIGINAL ARTICLE

Developments in integration of advanced monitoring systems

Przemysław Oborski

Abstract Monitoring is an important part of manufacturing process control and management. It plays a crucial role in ensuring agility in a manufacturing system, process robustness, responsiveness to client demands, and achievement of a sustainable production environment. Recent developments in information systems and computer technology allows for the implementation of new philosophies that integrate various monitoring applications into one complex system connected through company-wide IT systems and with systems operating throughout the whole supply chain. This paper reviews developments in the area of advanced monitoring and integration. Research on new approaches, standards, developed solutions, and company applications are presented. New directions of research and development in all areas of advanced monitoring and implementation of recent IT solutions are discussed.

1 Introduction

Manufacturing companies competing in the global market are forced to continually maintain manufacturing quality and products improvement. Additionally, at the same time, it is necessary to also reduce prices and shorten production times. These considerations have become even more important since the financial crisis of 2008 [1]. Meanwhile, product

P. Oborski (✉)
Warsaw University of Technology, ul. Narbutta 86, 02-524 Warsaw, Poland
e-mail: p.oborski@op.pl

complexity is rapidly increasing and new hard-to-manufacture materials are being continually developed. There is growing sophistication in production processes along with technical risks [2]. Today's product development process, production environment, and equipment must perform at levels that seemed impossible just a few years ago [3]. The expectations of customers for increased safety, product quality, availability and agility, together with the need to meet governmental, business, and social requirements elevate the speed and pressure on manufacturers to manage their assets more effectively [4]. The necessity to maintain—and very often increase—operational effectiveness whilst simultaneously reducing capital and operating expenditures is an ongoing challenge for manufacturing enterprises [5]. To address these demands, a significant change is necessary from past culture, processes, management and organisational concepts [6].

Strict cooperation of companies with various competencies and production resources is necessary especially in the case of small and medium enterprises [7]. At the same time, business risk is growing rapidly and needs to be better addressed. Legal and financial responsibility for defective products or poor quality has never been higher. Ineffective businesses have to close or move to lower cost countries [8]. Such factors are forcing manufacturing companies towards a more rapid development of production systems [9]. Some of the most important changes are coming from the area of integration of information flow through sophisticated IT solutions and connection with advanced monitoring and supervision systems [10]. This has become especially important in an age of rapidly developing Internet-based applications, cloud computing, etc., which allows for the integration of company systems into the supply chain in one system that can even include integration of shop floor control [11].

Looking directly at the production shop floor, we can see that there are a number of ideas that have been developed for

manufacturing systems organisation, including agile [12], holonic [13], fractal [14], and others. All are based on the common concept of a distributed and dynamic shop floor, where autonomous assets interact to overcome disturbances and problems during order performance. In this kind of system, it is clear that monitoring plays a fundamental role in supporting the operation of particular machines, process, and supervision of manufactured parts [15]. Such autonomous monitoring of assets has to be integrated into one flexible, open, and robust system that allows for a sustainable production environment. The development of integrated monitoring and supervision systems is also important from the so-called green manufacturing, a new research area that focuses on the reduction of energy consumption [16, 17].

The aim of this article is to present a review of new approaches to integration of monitoring and supervision functions into one system connected with machine control, shop floor control, company IT systems, and with other company systems in the supply chain.

2 State-of-the-art: overview

Most research in the field of monitoring is focused on stand-alone solutions that are not connected in one complex system as shown in a review by Byrne et al. [18] and Teti et al. [19]. New developments in computer technology and data processing, new standards, solutions and advances in programming technology create new opportunities for the integration of monitoring systems. The costs for monitoring implementation is decreasing because of miniaturisation, multifunctional sensors, micro-electro-mechanical systems (MEMS) application, embedded intelligent solutions development, implementation of new data processing standards and lower data-processing equipment prices. With these factors in mind, the potential for development of integrated advanced monitoring systems is very high. Rapid development of IT systems [20], new solutions like cloud computing [21, 22], and multiagent applications [23] allow currently for the practical implementation of monitoring integration into one distributed system.

There is also a growing need for integrated advanced monitoring systems that can support production and supply chain management, optimisation of production processes, and for advanced control systems that would allow for the evaluation of product quality based on an analysis of monitored manufacturing parameters. As such, real breakthroughs in the philosophy of monitoring systems development and application seem practical and highly likely.

A detailed review of the state of the art in this area and related technologies that are necessary for integrated monitoring systems development are presented and analysed in the paper. Expected research directions are also presented and discussed. Developments in *monitoring and supervision*

systems are analysed in Section 3, which also contains an overview of state of the art in the main areas of monitoring systems application, such as *condition monitoring systems* (Section 3.1), *shop floor monitoring* (Section 3.2), *monitoring in maintenance systems* (Section 3.3), and *integration of monitoring with control functions* (Section 3.4). Next, Section 4 provides a concise review of the latest advances in research on condition monitoring systems—*development of condition monitoring and supervision systems*. Finally, Section 5 provides a comprehensive state-of-the-art review with detailed analysis about necessary and possible research and development directions in the integration of monitoring into a coherent system—*developments in integration of monitoring systems*.

This main part of the paper is divided into the particular spheres necessary to build an integrated monitoring system. The following subsections focus on: *general direction of development* (Section 5.1), *development in technical areas of monitoring integration* (Section 5.2) containing sensors, computer numerical control (CNC) controllers, real-time systems, and embedded systems analysis. The next subsection is on *new approaches in systems areas of monitoring integration* (Section 5.3) and includes the MTConnect standard and cloud computing. The last subsection is an overview of *software solutions for integration of monitoring systems* (Section 5.4). Integration based on a client–server architecture, solutions based on supervisory control and data acquisition (SCADA) systems, and multi-agent technology is comprehensively analysed. Special stress is place on multi-agent systems and their major challenges that have not yet been well addressed in research, but give number of advantages important for manufacturing IT systems.

3 Monitoring and supervision systems

3.1 Condition monitoring systems

The ability to meet increasing customer expectations will require more common implementation of monitoring and supervision functions into machining processes and machine tools. Such functions will have to be integrated with shop floor control and companywide IT systems operating at the management level [24]. Research are carried out on integration of tool and machine condition monitoring with CNC control by allowing access to internal signals in the numerical controller, such as motor power, motor current, or additional measured signals like, vibrations, position, etc. [25]. Research has also looked into integration of various monitoring functions in one system.

Currently, however, most monitoring devices are implemented as local, stand-alone solutions [19]. In the near future, in order to meet client requirements, monitoring will have to allow for ongoing supervision of the machining process,

machine, and produced part parameters. The collected information will be used for production process online control. Further, this production history will need to be archived as a history of the particular workpiece. The effective implementation of complex monitoring and supervision systems raises some significant challenges. One of the most important is obtaining timely, reliable information on the state and conditions of the manufacturing process and machine tool. Another is to analyse the obtained data in order to diagnose a problem [26] (Fig. 1).

Then, based on the diagnostic information, the decision on a possible action should be performed automatically or by the operator. In addition, information about the process and machine tools, detected problems, decisions, and control activities carried out should be archived in the form of an order history. This history shall include comprehensive information about all aspects of the part and machining. This should allow an analysis of any causes of malfunctions occurring during operation of the product, or potential faults that can result from the manufacturing process. This is particularly important in the manufacture of vital and expensive parts, such as in the aviation industry or energy field. For example, in 1997, the AIA report on Rotor Integrity Sub-Committee stated that approximately 25 % of the faults in air engines are caused by irregularities in the manufacturing process [19]. This approach will be increasingly important with the constantly progressive development of machining processes, processing and analysis of data, and the growing complexity of products, Moreover, in the future, this approach will also be increasingly important for less complex manufactured products in other industries.

3.2 Shop floor monitoring

Monitoring and supervision functions should be a part of sophisticated information systems. Such systems should allow for control of all aspects of the production system, including machine tool operation, production process, manufactured product, and performed orders [27]. The system has to monitor parameters that are important for proper operation of machine tools, production process, etc. Finally, the system should facilitate decisions that address discovered problems, avoids losses, or reduce risk. Decisions can be taken automatically or by operator that is supported by the IT system (Table 1).

A significant problem in process, workpiece, and machine tool condition monitoring is the large number of highly variable parameters. A high sampling frequency is dictated by high-speed tool or workpiece rotation, movement of machine elements, etc. [28]. To manage this problem, data has to be collected locally and analysed by dedicated algorithms to select important information. Such information can then be used for further action. The following table presents examples of parameters that can be monitored in a manufacturing system and decisions that can be taken to solve discovered problems (Table 2).

The parameters provided above concern one machine, the process performed on it, and on one workpiece. A manufacturing system, however, consists of a number of cooperating machines. Each machine can be of a different type, performing different processes, and use a number of various tools. Similarly, there are a wide variety of manufactured parts that can be produced by different processes using various machines.

Information obtained from analysis of collected data should be used in the next step to take control decisions that will result in a particular action to solve a discovered problem. A decision-taking action is usually not a standard action. Sophisticated algorithms based on artificial intelligence or examination of databases with suggested solutions are very often required. This may involve performing negotiations between interested objects, machines, modules, etc. This can be especially important for changes to the manufacturing process or production schedule.

The actions proposed in the above table should be taken locally as the result of a locally performed decision process. The decentralisation of the decision process is necessary to increase system efficiency, stability, and resistance to disturbances [24]. This has to support flexibility in the system and an openness to configuration changes [29]. The centralisation of control decisions was one of the main problems of past flexible manufacturing systems and one of the main reasons behind their limited implementation [30].

3.3 Monitoring in maintenance systems

An important part of a monitoring application is the maintenance systems. Current manufacturing systems have to work
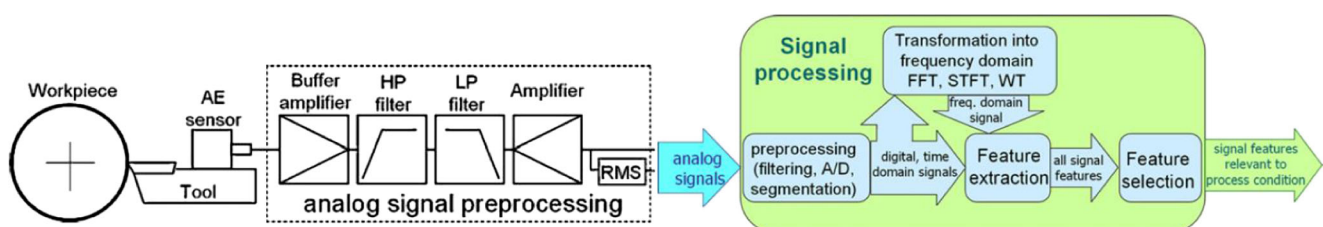

Fig. 1 An example of signal processing in a monitoring system (based on Teti et al. [19])

Table 1 General requirements of a shop floor level monitoring system

Requirements	Characteristics
Data acquisition	Data acquisition from monitored process and machines.
Monitoring of manufacturing process, machines, and parts	Analysis of data from manufacturing process and combining this with set values. Discovery of problems. Taking control decisions, if necessary, when deviations are detected.
Processes control support	Support for taking and performing control decisions aimed at realising production plan and disturbance elimination.
Data archiving	Registration and archiving data from machine, process and part monitoring.
Easy change of configuration	Easy reconfiguration of the system (changing functionality, adding new machines, changing system structure, etc.) for reconfiguration of the manufacturing system.
Flexibility	Flexibility in meeting different orders, also orders that need functionality not supervised during system development and that have to be added.
Resistance to disturbances	System stability and resistance to disturbance, ability to take local decisions to eliminate influence of disturbance on system performance.
Easy to use	User-friendly system with intuitive decision support, easy to reconfigure and add new functionality.
Operating in distributed environment	Operating in distributed environment consisting of computers, controllers, mobile terminals, and equipment connected by various kinds of computer networks.
Independence in computer operating system	Ability to operate with various control equipment and on various computer operating systems.

with zero breakdowns. The reliability of the production system is of crucial significance during cooperation in the supply chain, that, nowadays, usually works in a just-in-time environment, without stores, and without reserves [31] (Fig. 2).

One of the important driving forces pushing forward research on development of monitoring systems was the necessity to deliver information about the status of a machine and processes in maintenance systems [32]. Currently, using a

reliability maintenance approach needs advanced monitoring systems that have to deliver predictable information about possible problems, lower functionality, or breakdowns that can appear in the near future [33]. Such an approach requires complex integrated monitoring systems that analyse online all crucial machine and process parameters. The idea of E-maintenance thus developed with the emergence of the Internet and cloud computing [34]. This concept is based on

Table 2 Examples of parameters that can be monitored in manufacturing system and decisions that can be taken to solve discovered problems

| Monitored object	Examples of parameters that can be monitored	Examples of decisions that can be taken to solve discovered problems
Machine tool	• Machine tool or critical components condition monitoring • Thermal errors, geometric and dynamic parameters • Vibrations, temperature, acoustic emission • Proper operation of mechanisms • Maintenance activities • Time of work (preparation, processing, breakdown, maintenance)	• Compensation of dimension and geometry changes caused by temperature changes or process forces. • Changes in process parameters, eg., to avoid vibrations or increase temperature. • Starting of maintenance activities. • Testing to analyse discovered problem or to check proper operation after maintenance. • Emergency stop, eg., in machine breakdown. • Working with limited functionality. • Proposing action plan to solve the problem.
Machining process	• Tool condition monitoring • Temperature, vibrations, acoustic emission • Process efficiency • Process parameters	• Process optimisation – process parameters changes. • Changes in process parameters, eg., to avoid discovered problems or minimise loses. • Support operator by suggestion of optimal parameters suited to actual process condition. • Emergency stop, eg., in the case of tool breakdown. • Proposing action plan to solve the problem.
Workpiece	• Geometry (dimensions, tolerances) • Surface parameters (roughness, quality, geometric parameters) • Material parameters (temperature, hardness, stress) • Manufacturing data: time (preparation, processing, waiting), machine and tool(s) number(s), operator, etc.	• Selection of optimal process parameters. • Recording history of manufacturing: machines, tools, parameters. • On-line optimisation of process parameters according to measured part parameters. • Optimisation of production parameters – time, schedule, batch size, etc. • Proposing action plan to solve the problem.
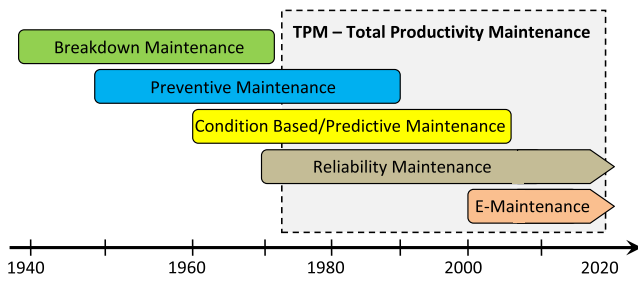
Fig. 2 Development of maintenance systems

maintenance systems that manage and exchange monitoring information/data via the Internet. The development of E-maintenance will force integration of monitoring and supervision into one complex distributed system operating over an entire shop floor or even throughout the whole supply chain [35, 36]. Research shows, however, that current IT-based maintenance systems have not been implemented yet to any large extent by manufacturing companies. Such systems are still considered in most cases as an additional cost, not as a business opportunity. Maintenance systems usually are only implemented when companies understand that proper maintenance allows for systems and process optimization, and not only problem prevention [37].

The situation is different in the process and power industry, which tends to be dispersed over large areas and production devices very often operate automatically without operator supervision. In this kind of business, remotely operated maintenance systems are necessary (Fig. 3).

Monitoring in the process industry is usually based on SCADA systems. They allow for data acquisition directly from sensors or PLC that control various parts of the production devices. The concept of remote monitoring and maintenance based on the idea of E-maintenance was first introduced by Lee [38]. It is helpful to the development of integrated monitoring for manufacturing, although it was developed mainly for maintenance systems in the process industry. The author proposed six functional requirements:

1. *Multi-sensor integrated monitoring and control system*: integration into one system, a number of sensors and local control devices responsible for operation control of various production devices.
2. *Communication*: integration of geographically dispersed machines through computer networks.
3. *Data abstraction*: only relevant data are to be transmitted through the network.
4. *Knowledge acquisition and learning*: there is a need for intelligent tools to acquire and organise data on the manufacturing processes at one site to share it with other sites. The whole system should be capable of learning the behaviour of users at different sites.
5. *Natural language translation*: tools to automatically translate text into other languages.
6. *Telemaintenance and diagnostics*: to facilitate work by technical personnel to perform diagnostics on machines that are geographically distributed.

Based on these requirements, a framework for web-enabled e-maintenance systems was proposed [39]. Ever since the emergence of a number of remotely integrated maintenance systems, some have used intelligent agents and multi-agent technology [40–44]. An example of such a system is the intelligent control-maintenance-management system (ICMMS) based on a multi-agent concept. The aim was to apply it to monitor the equipment of an automation system of a hydroelectric generating unit [45]. An interesting solution is a condition monitoring multi-agent system (COMMAS) that was developed and applied to monitor a gas turbine start-up sequence [46]. A relevant review of the integrated maintenance systems developed mainly for process, chemical, and power industry has been done by Campos [24].

Fig. 3 Integration of e-maintenance, e-manufacturing, and e-business systems [34]
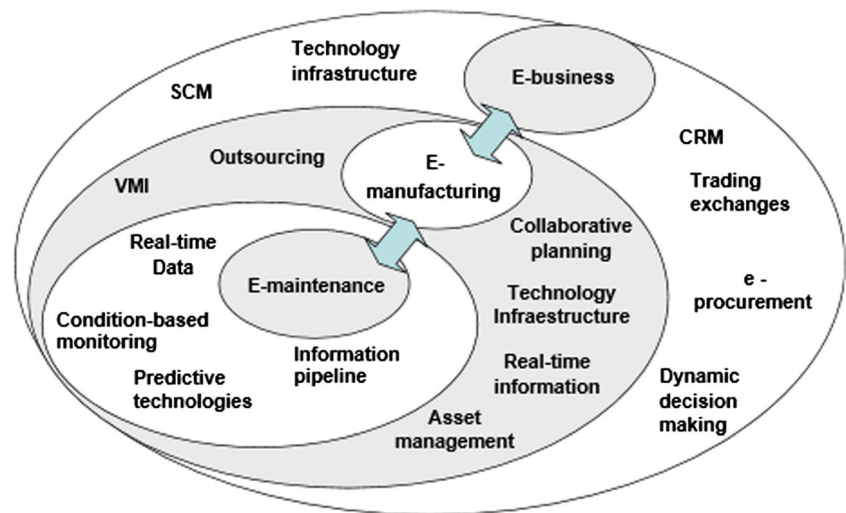
3.4 Integration of monitoring with control functions

Advanced monitoring and supervision system for manufacturing processes should integrate a number of sophisticated functions starting from data collection, through analysis, and until decision taking to identify problems and propose necessary action. Usually, a system only plays an information role for an operator working with a particular process. A system gives information about a problem to an operator who has to then take a decision and execute an appropriate action [19]. However, to meet the requirements of advanced manufacturing, a monitoring system have to be integrated with companywide IT systems and should be connected with control functions that allow for taking of actions according to identified problems [6]. The functions integrated in the frame of an advanced monitoring and supervision system can be presented as a process (Fig. 4). This process starts with a collection of data by sensors, continues through problem detection, and engages until presentation of information about a detected problem for the case of a monitoring system. If control functions are added, the response to the detected problem is the decision about an action and finally an action that is performed to solve the problem. The main functions of a monitoring and supervision system model are presented next.

3.4.1 Signal acquisition

Signal acquisition is usually done through specialised cards that collect sampled data from sensors in real time. Sensors are dedicated to taking data from a particular part of a process, machine element, or part of a measurement device. Collected data has to be roughly prepared and then filtered and analysed to take from the signals any information that is necessary for further analysis. This is difficult due to typical high frequencies in probing and the large number of disruptions caused by a machining process and machine tool operation.

3.4.2 Detection

Detection is an important and difficult part of monitoring. Its aim is to analyse data collected from sensors to determine if there are any abnormal signals that can inform about a problem in the monitored process, part of a machine, or product. Special intelligent algorithms should be used to allow efficient and correct detection of changes in monitored data. This should allow for detection of changes that inform about present and possible future problems.

Fig. 4 Model of advanced monitoring and supervision system connected with control functions
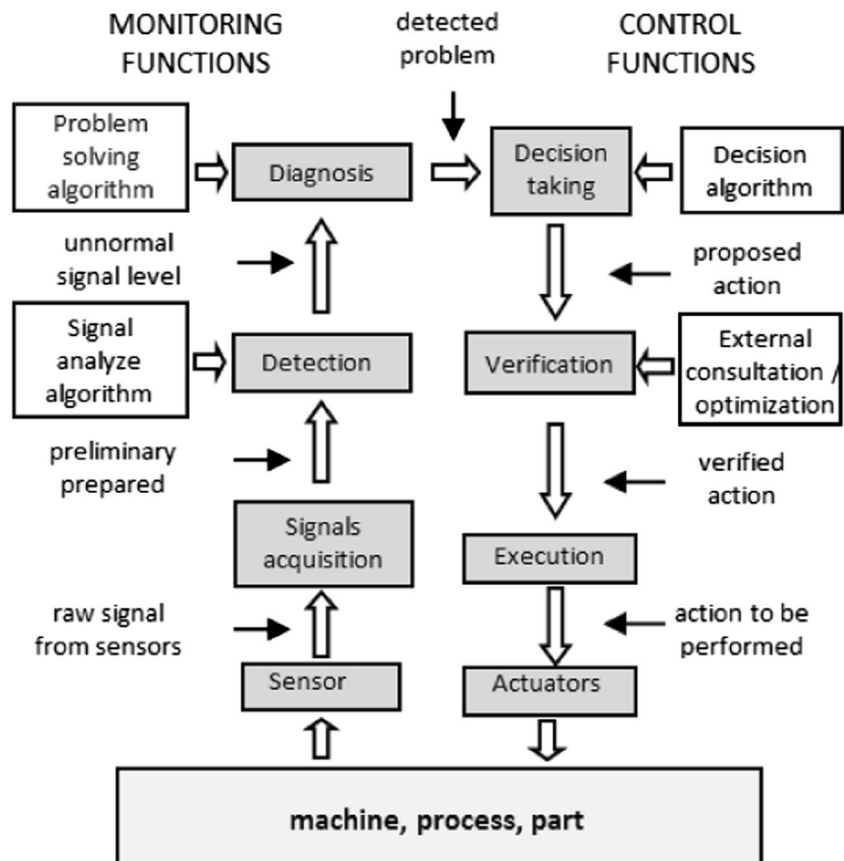
3.4.3 Diagnosis

The aim of diagnosis is to clearly determine the problem that has occurred in a particular machine process or manufactured part. This requires the use of a dedicated algorithm that can be based on artificial intelligence or a knowledge base that allows for problem solving. Information about a detected problem can then be presented to operator or a control action can be performed.

3.4.4 Decision taking

The decision-taking module is part of control functionality. It should be responsible for preparing the most optimal action that reacts to a detected problem. It has to be based on an advanced decision-taking algorithm. The proposed action can be verified by external consultation with either a software coordinator or by a machine operator.

3.4.5 Execution

The execution of a control action is the last activity in the process of monitoring and control. This is aimed at performing an action that eliminates the problem or reason for the problem detected by the monitoring system.

4 Development of condition monitoring and supervision systems

The rapid development of methods, tools, monitoring and supervision systems, combined with sensors and computing technique improvement allows for more efficient acquisition of information about processes, machines, and parts [47]. The entire spectrum of processing and data analysis methods is based on both direct and indirect measurement. Parameters such as forces [48, 49], load drives [50], current [51], cutting forces [52], torques [53], temperature [54–56], acoustic emission [57], sound signals [51], noise and surface acoustic wave [58], vibrations [59, 60], or vision [61, 62] are used for this purpose. Data acquisition uses various kinds of sensors: mechanical, piezoelectric, optical, laser, etc. [63]. Research is moving towards wide implementation of sensors based on microtechnology embedded in machine parts, drivers, chucks, tolls, and machined parts. Examples of such approaches can be found in [64] and [65]. Such a solution connected with special control devices is called intelligent devices. Some physical phenomena are also used for acquisition of necessary data [66]. These devices allow for the development of sensorless applications [67–69].

Obtained data needs to be subjected to advanced processing and analysis methods using multilayer neural network-based algorithms, fuzzy logic, and analysis in the field of time and frequency [70]. A monitoring system can increase reliability and robustness in terms of managing disturbances, and is usually based on data from several independently measured sources. Some examples include a cutting force, torque, acoustic noises, and vibration. One of the key problems lies in achieving advanced data processing of the obtained signals. It has to allow for the extraction of relevant information useful for further analysis. As a result of analysis, signals that carry information have to be separated [71]. Such information can be compared with an analytical model of the machine, workpiece, or manufacturing process [72]. Additionally, models based on artificial intelligence can be used for this purpose [73]. Based on advanced algorithms, the current state of a process is specified and predictions are made about future behaviour [63].

A literature review shows that most research focuses on monitoring of the following areas:

- Tools and tool holders: operating conditions—tool wear and tool breakage, geometry, temperature, vibrations [74–79], and also for micro milling [80–82]
- Chipset: chips formation, chip breaking, and chip removal [83–87]
- Machining process: disturbances, errors, variables, process status, and parameters [64, 88–93]
- Manufacturing part: surface of the part, surface roughness, surface condition, and parameters [94–101]
- Machine: the machine status, drives wear, spindle bearings damage, total preventive maintenance (TPM), work condition (vibrations, temperature, and machine distortions) [102–106].

A comprehensive overview of research and solutions was done by a CIRP working group in 2010 [19]. To what was mentioned, it is necessary to add monitoring for manufacturing parts geometry and quality. Examples of research in this area can be found in the following papers [101, 107–109]. An interesting area of research is assessment of the machinability of hard-to-machine materials supported by process monitoring [110]. The so-called green manufacturing also offers a new research area aimed at reducing energy consumption. An example comes from the development of automated monitoring of machine tool energy usage in correlation with the operations being performed [111].

Based on monitoring data, adaptive control systems [112] and optimisation systems [113] can be developed. Monitoring and supervision systems often have modules supporting decision-making. Those modules usually are based on neural networks [114–116], genetic algorithms [117], fuzzy logic [118], or knowledge and expert systems [119]. They allow for automatic decision taking on the basis of analysed signals changes or support of the operator through suggestions about

an optimal decision. Another important area of research is focused on the social aspects of monitoring systems that have to cooperate properly with machine operators [120–122].

Tool and machine-condition monitoring systems are becoming increasingly advanced. There are industrial applications, particularly in the case of mass- and large-series production with stable machining parameters. However, the increasing demands on the quality of manufactured products, reliability of the production systems and processes, and the need to reduce costs is pushing towards the monitoring of selected areas of the manufacturing process by dedicated, advanced supervision systems. Manufacturing companies are increasingly interested in not only the monitoring of one or two areas, but in having a complex, holistic approach to overall manufacturing supervision.

5 Development in integration of monitoring systems

5.1 General direction of development

A significant problem in manufacturing systems is the challenge of providing effective monitoring of a large number of highly variable parameters. Control of these parameters and adequate reaction to improper values changes is necessary to maintain a high efficiency in machine tools, production processes, and product quality. This is now critically important for effective management of production process, manufacturing systems, and the product production process [123].

Another key area of concern is management of the complex history of a manufactured part. Such a history should consist of information from the monitoring of the machining process, along with machine status and workpiece parameters. It is very important to integrate monitoring with other company IT systems, like the CAM, shop floor control, maintenance, and management systems [10]. From a global point of view, the development of manufacturing systems is moving in the direction of large, distributed, flexible virtual organisations focused around supply chains that are connected by IT systems that allow for full integration of the information flow [20, 124].

In such approaches, integrated monitoring and supervision systems connected to supply chain-wide IT systems will play a crucial role. The integration of machining process monitoring and supervision requires a connection into one system of various applications, which are currently developed independently by individual research teams. A comprehensive, holistic approach to the problem of monitoring would have several advantages. This integration would allow for comprehensive monitoring of all relevant parameters: process, tool, machine, and workpiece.

The data collected and processed by multilevel analysis would allow for a holistic picture of manufacturing process and the history of the product formation. This would also provide a synergy effect, where the results of the measurement of some parameters and areas would provide for more relevant inference in other areas. For example, detecting changes in the cutting forces, machine vibration, and changes in a workpiece surface would allow one to learn about both the cause of a phenomenon and also the final impact on product quality. This knowledge would open up the potential for identifying the causes of a problem, its elimination, and proper treatment towards a final product (Fig. 5).

An integral part of the supervision systems are sensors. Similarly to data processing and decision-making, they should be integrated into one system. Such an approach should allow for cost optimisation and simplify data acquisition. The sensors should allow for modular construction of the system, based on a common architecture for the interchange of data. This would make it possible to implement various items, such as sensors, equipment, and applications for data acquisition and signals processing. Such systems should also allow for easy integration with machine control systems, in order to allow control data acquisition and implementation of the control functions. The integration of monitoring and supervision systems potentially gives the ability to reduce cost, through the use of common solutions that could be standardised. Some parts could be installed and offered by machine tool producers. The need to implement the integration of monitoring into one system is not only logical from a theoretical point of view, it also meets business expectations and industrial companies that are beginning to look for complex solutions that are currently not available [126].

5.2 Development in technical areas of monitoring integration

Although researchers have sounded the alert for the importance of integration of monitoring functions into one system [127], most current applications for manufacturing systems are dedicated to supervising changes of only a few selected parameters [19]. Good examples of such systems are monitoring of a tool condition system [80] or machine temperature monitoring based on compensation of thermal deformations [128]. The following sections discuss the most important components in monitoring systems integration.

5.2.1 Sensors

Sensors that are an integral part of the monitoring system are also some of the most expensive and difficult to implement devices. A significant problem is implementation of sensors in a location to generate an appropriate signal, such as at the end of a cutter. It is especially difficult when several sensors have to be installed [129]. It is also important to consider the role of communication between sensors implemented in machine

Fig. 5 Web-based integration of maintenance/monitoring system concept [125]
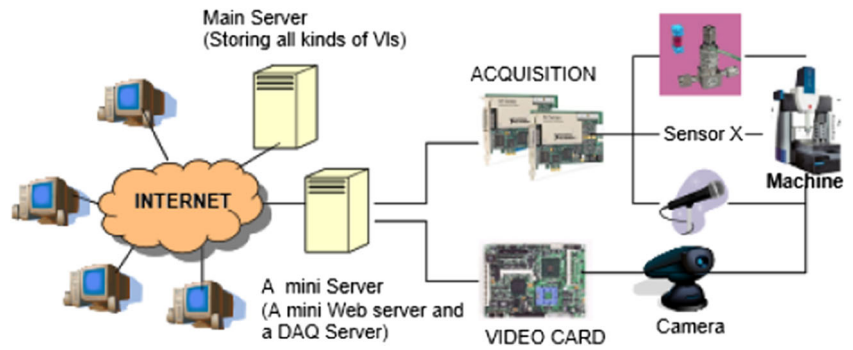
elements, tools, and workpieces and from the other side in monitoring systems and machine controllers [130–132].

Currently, there are modular solutions that are commercially available [129, 133]. Using these systems, it is possible to build easy-to-reconfigure measurement chains or even ready-to-use solutions suited to particular machining processes [134]. Research in this area is moving towards the development of inexpensive sensors, and also wireless sensors [135] that are integrated with processing units and are called smart sensors [136]. These smart sensors allow one to measure a number of parameters. Such sensors should make it possible to implementation into machines, mechanisms, and tools as part of embedded solutions [137, 138].

A very important direction is the development and application of MEMS technology, which will allow for miniaturisation and cost reduction [139, 140]. Microsensors based on MEMS can be equipped with autonomous power, memory cells, analogue amplification, converter, etc., and can be easily adapted for various applications [141] (Fig. 6).

5.2.2 CNC control

During the last several years, a significant stress has been put into research on the development of intelligent, flexible, and easy-to-configure open CNC control systems. In such systems, implementation of monitoring functions has to be easier than in standard CNC control systems. A stress is put on integration of control, monitoring, and CAD systems to obtain possible offline or even online optimisation of a process [142]. However, in most developed approaches, solutions and standards still have to be implemented in practise.

At the same time, an integration of monitoring applications with commercially offered CNC control has been developed and implemented in industry. Special dedicated monitoring interfaces have been developed by CNC producers allowing for the integration of some monitoring functions via the human machine interface of CNC control [143]. The development of an open CNC control makes integration of monitoring with control systems easier than in the past [144, 145]. It is possible to now add customised monitoring functions, connecting it with signals measurement and implementation

Fig. 6 Reconfigurable multi-sensor monitoring system [19]
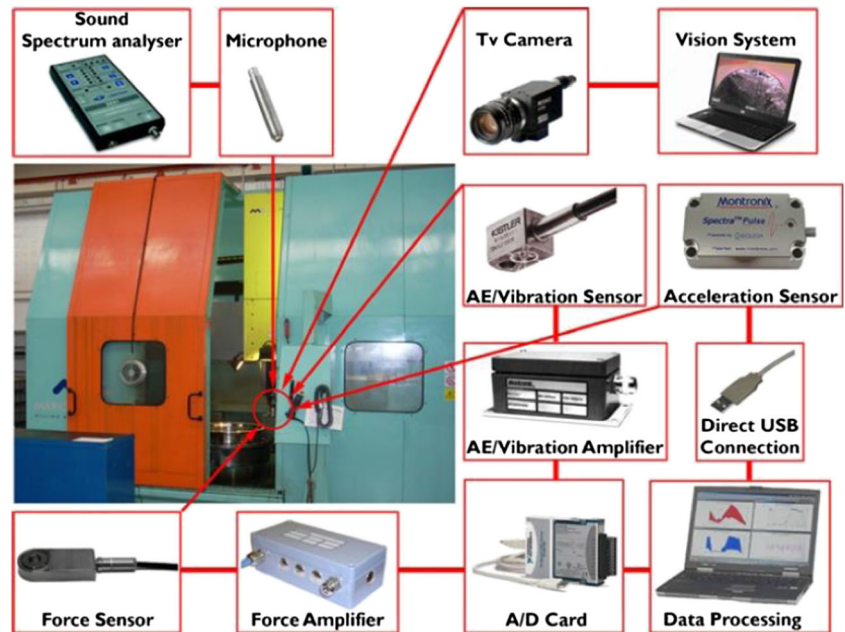
of control functions allowing for optimisation of machine operation or processes [25, 142, 146].

A very interesting direction in CNC development is research on applying a multi-agent philosophy that allows the implementation of intelligence at various levels of the control system [147]. An example is the MADCON system that was developed to simplify the interaction between hardware and software functions, simplifying system customization and allowing for simple integration of control and monitoring functions [148]. However, in spite of a large number of studies, an open CNC control systems, these systems are generally only used in special or retrofitted machines. They are still not used in the mass production of machine tools. Therefore, integration of monitoring and shop floor control systems still have to be based on standard CNC control systems and function offered by their producers.

5.2.3 Real-time

Real-time systems (RTS) have to be applied in all process and devices when system operation depends not only on the logical results, but also on the time at which these results are achieved. Real-time technology can be divided into soft- and hard-real-time. In soft-real-time systems, delays are acceptable, but they increase the cost of system operation. In hard-real-time systems, delays or errors are not acceptable, because such delays can destroy a machine, system, or be dangerous to peoples [149]. In manufacturing, machine control and monitoring usually has to work under hard-real-time constraints. Usually, monitoring systems are built in a hierarchical way. Lower layers are responsible for signal acquisition, and analysis is done by software and hardware working as a hard-real-time system. This is implemented on specialised computer cards based on dedicated DSP processors, dedicated real-time operating systems, and special software [150]. To connect monitoring with a control function, for example to optimise or for process control, most systems have to be built as a real-time system. Apart from acquisition devices that consist of sensors and measurement cards, special controllers, like an advanced PLC or industrial PC have to be used. Controllers operating in real-time operating systems are connected with each other through real-time industrial networks. Software for data analysis, decision support, and control tasks have to work under real-time conditions. Implementation of real time into monitoring systems requires the use of special dedicated devices, like measurement cards operating in real-time conditions. In most cases, solutions connecting sensors, data acquisition, and controllers for rough analysis can be built as an embedded systems [151]. This allows for miniaturisation and radical cost reduction.

5.2.4 Embedded systems

Embedded systems are computer systems with dedicated functions within a larger mechanical or mechatronic system. Very often, they work under real-time computing constraints. Such systems are embedded as a part of a complete device. They consist of hardware such as processors, memory, control software, and often mechanical parts, like sensors or actuators [152]. Nowadays, most products, such as telephones, cameras, cars, washing machines, etc., are based on such systems. In the past, embedded systems were built on a small scale and with limited functionality. Current advances in microelectronics and software allow embedded systems to be composed of a large set of processing elements [153].

Development trends are moving towards significant enhanced functionality, complexity, and scalability [154]. Based on wired and wireless networks, connections are being built for large-scale distributed real-time embedded systems (DRES) [155]. Such embedded computing and information technologies have become an enabler for further development of monitoring and control systems. Basing on large-scale distributed real-time embedded systems, it will be possible to build complex integrated monitoring systems to monitor the complete production process. This includes being able to integrate with the control systems of machines and the shop floor.

At a lower level, monitoring systems in real-time embedded solutions will allow for development that includes intelligent sensors combined with data analysis applications. An important research area is in miniaturisation and embedding mechanical systems based on MEMS. Such micro systems could be easily applied to machines, handles, tools, or even manufactured parts.

5.3 New approaches in systems areas of monitoring integration

5.3.1 MTConnect

A project called MTConnet was started in 2009 by the American Association for Manufacturing Technology being a result of activity focused on integration of monitoring systems [156]. Its goal was to develop an open communication standard between different types of equipment and systems used in manufacturing systems. The aim of the standard is to allow data to be exchanged between different applications and have these applications run over the Internet. The MTConnect standard defines communication between monitoring and control devices and information systems. It is based on the XML standard. Currently, the development of an overall standard is being established especially for this purpose by the MTConnect Institute (http://mtconnect.org/; Fig. 7).

Fig. 7 An example of
MTConnect object model [157]
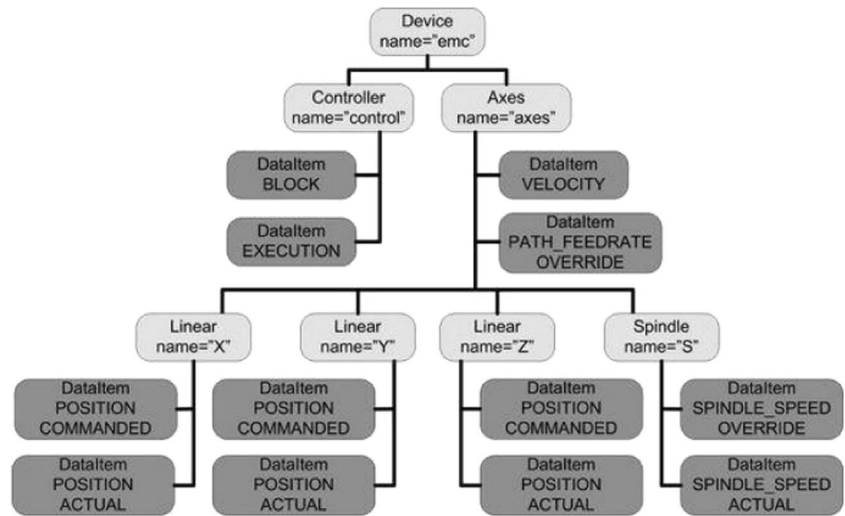
The possibility of easier and cheaper integration of solutions offered by different producers into one system is an advantage of the MTConnect standard. It allows for easy data exchange independently of hardware platform and operating system. A disadvantage of the standard is that it is based on the ICP/IP protocol. This results in a limited data transfer rate and makes it almost impossible to build systems operating under real-time constrains.

There is much research being done based on the MTConnect standard. The aim is to develop integrated monitoring and control systems for manufacturing processes and machine tools. An example is the application of the MTConnect standard to exchange of data between CNC control, a shop floor control system, a companywide IT system, and a special optimisation application. Optimisation of the manufacturing process through comparison of real machining parameters with a CAD/CAM model and according to this, modifying machine parameters is the aim of the system [157].

Another similar system, also based on the MTConnect standard, was developed by Ridwan [158]. It allows for the integration of information from different monitoring systems, analysis and visualisation. Data from the monitoring system is submitted using a standard STEP-NC to the driver, which conducts an optimisation process (Fig. 8).

The project is currently in the research phase, but demonstrates the trend towards monitoring and control integration based on recently developed standards. An interesting example of integration based on MTConnect is a monitoring system for of machine tool energy consumption [111].

5.3.2 Cloud manufacturing

Data processing via so-called cloud computing is one of the fastest growing areas of IT systems [159]. According to the definition by National Institute of Standards and Technology (NIST) in the USA), cloud computing is: "a model that allows

for ambitious, tailored to needs, attach to the common area network computing resources, that can be shared instantly and released with minimal effort and minimum interaction with the entity offering services" [160] (Fig. 9).

A number of research projects are aim at application of the cloud philosophy to manufacturing systems. The most advanced project is funded under the FP7 EU-project ManuCloud [21]. The aim of this initiative is to develop a model of service oriented, customer centric, and demand-driven manufacturing systems based on cloud computing.

The ManuCloud project is a new direction in development in the area of high-speed, long-distance industrial control systems, and flexible cloud-computing applications for manufacturing. Based on this philosophy, solutions will be able to integrate monitoring into one system that connects different companies together along the whole supply chain
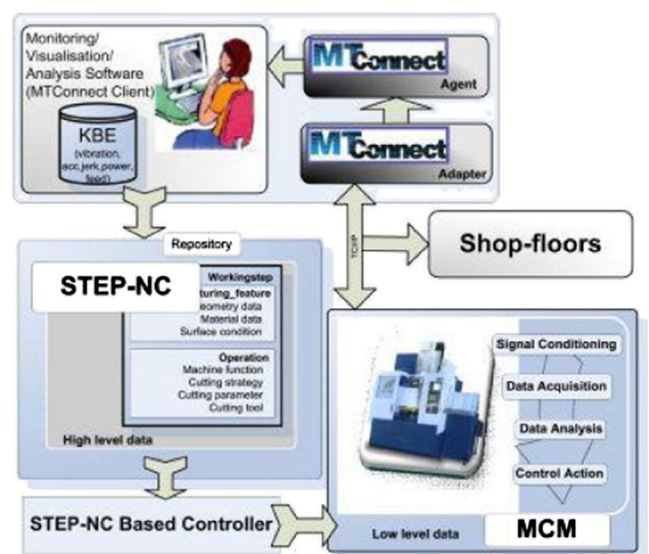

Fig. 8 Structure of integrated monitoring and optimisation system based on MTConnect and STEP-NC standard [157]
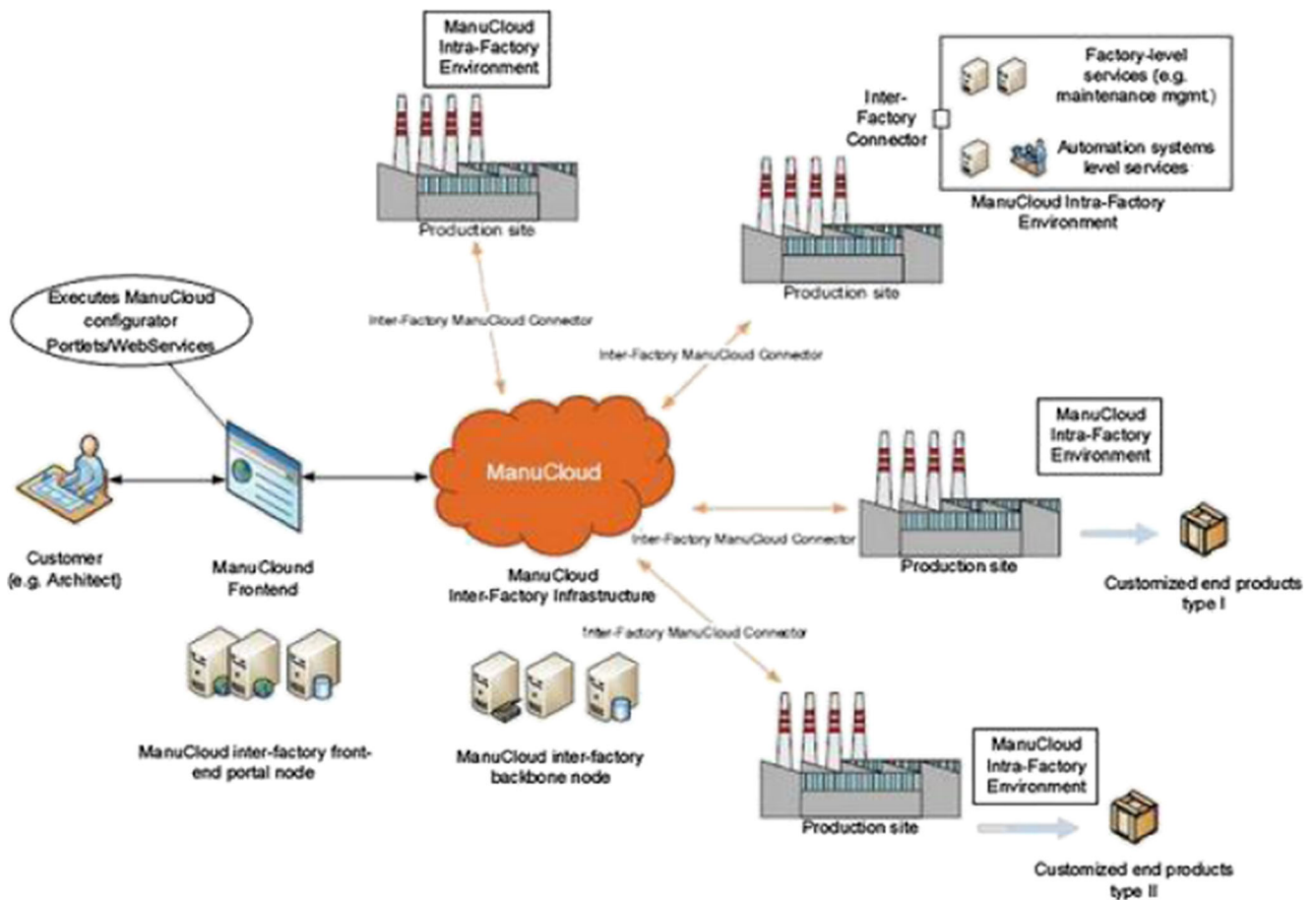
Fig. 9 Cloud manufacturing architecture-ManuCloud project [22]

of a production process. Other examples of research in the area of application of cloud computing to manufacturing include [161, 162].

The rapid development of cloud applications in most domains, such as for telecommunication, programming, management, and private life will put increasing pressure on manufacturing to meet similar expectations. Cloud manufacturing will most likely develop in the direction of data processing, orders management, supply chain organisation, and also provide systems management and control by external suppliers. A key aspect is the integration of monitoring and control of machines and production systems. The implementation of remote order management and outsourcing in manufacturing based on cloud manufacturing will require remote access to the results of completed orders, as well as the history of system capabilities and availability. This will be one of the key factors forcing both equipment suppliers and manufacturers to integrate monitoring applications into complex remotely available systems. An example of such a system is machine availability monitoring systems based on a cloud solution [163] or a monitoring system where data presentation is built as a cloud service [164].

5.4 Software solutions for integration of monitoring systems

5.4.1 Integration based on client–server technology

The client–server architecture was developed and popularised at the beginning of the 1990s [165] and is still the most popular architecture in IT systems. Company-wide IT systems are often built based on this concept, as well as various kinds of applications supporting manufacturing systems. Such systems are based on a common database or system core working as a server that offers services for other parts of the systems working as a client [166]. The advantages of such systems include well-known technology, a large number of systems, and programming tools supporting application development (Fig. 10).

Client–server technology allows one to build centralised applications where the server is a central part of the system, where most of the data operations are performed. Centralisation brings many advantages, including data integrity, a relatively simple architecture, and easy control of system operations [167]. There are, however, also significant disadvantages of a centralised structure. It has low flexibility, is difficult to reconfiguration, has complicated

Fig. 10 Centralised and decentralised systems
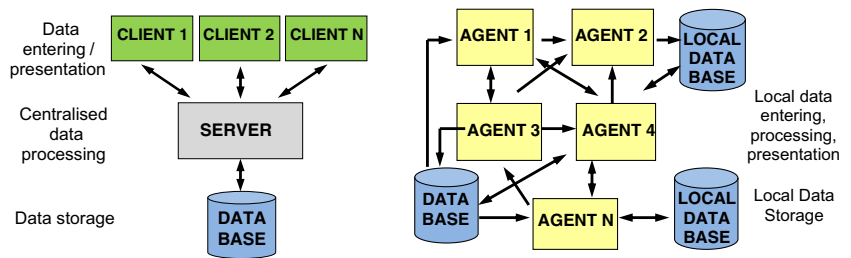
implementation of modular structures or various control algorithms, and high costs when building dedicated systems [168]. For manufacturing applications, an important disadvantage of client–server technology is a problem with implementation of real-time conditions necessary for processing data and control at the machine level. Servers operating on SQL or this kind of technology based on Unix or Windows operating systems are not real-time systems [169]. The need to connect the main system with separate applications makes building of a real-time environment very difficult.

Large integrated IT systems for the shop floor level in manufacturing are difficult to be built in client–server technology. As such, much of the information exchange between operators is currently done through paper reports for both control and monitoring. In practice, client–server technology can be built for dedicated control and monitoring systems that are static and do not often require changes such as adding new machines, adding functions, etc. This approach for large integrated solutions is expensive, inflexible, and is vulnerable to unexpected malfunctions. In modern, agile companies, where flexibility and the ability to make changes and decisions, client–server-based technology is really only suited for localised applications, rather than as a base for a large complex system.

5.4.2 Integration based on SCADA systems

SCADA are widely used in process industry monitoring and control [170]. There are large numbers of SCADA development environments offed by PLC producers and specialised software companies. Some open-source systems are also available [171]. A SCADA system has significant potential for integration in the manufacturing process. Such a systems, however, are built and optimised for control of relatively simple decentralised systems, like those in the process industry, pipeline systems, electrical grid, etc. [172, 173] (Fig. 11).

Security plays a crucial role in these systems, but usually the whole system does not need to operate under hard real-time conditions [175]. In these kinds of applications, a real-time system can operate just at the PLC level. Generally, SCADA systems do not meet the requirements of manufacturing systems, like flexibility, ability to implement complex algorithms for data processing and analysis, control for decision taking, and operation under hard-real-time constraints.

SCADA systems are based on PC operating systems, usually Windows or Unix. This makes implementation easy in an office environment were monitored data area are presented and control decisions are taken, by connecting it to the PLC. The main problem with these systems lies in integration and implementation into advanced monitoring systems, because of the difficulty in meeting real-time system requirements. As such, components need to be built separately based on PLC, industrial PC, etc., and then connected to SCADA components [172].

As a result, there are no advanced monitoring systems connected with control functions based only on SCADA in manufacturing. However, it is possible to build dedicated monitoring systems where some SCADA functions are used, especially for acquisition of simple monitoring signals, communication with a PLC, system interface (HMI), databases, alarm management, etc. These systems have to be supported by dedicated applications that allow for signal conditioning, processing and further evaluation by cognitive decision-making support systems for a final diagnosis that can be presented, archived, and managed by SCADA [176].

5.4.3 Multi-agent systems

Multi-agent technology is the name of a distributed artificial intelligence technique based on autonomous entities called agents. An agent is a logical object that can independently
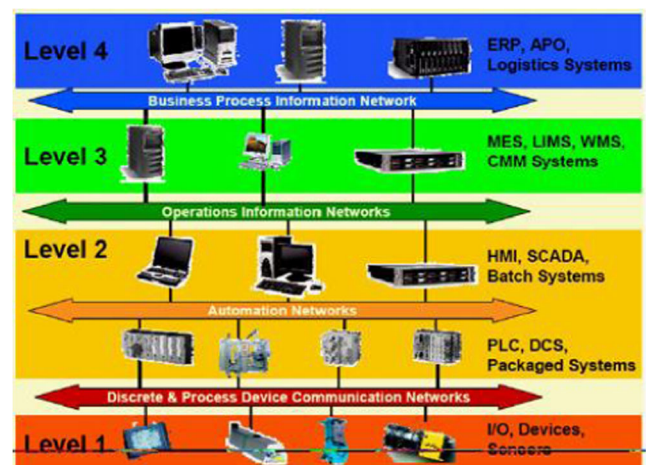

Fig. 11 SCADA systems in the industrial control hierarchy according to ISA '95 model [174]

perform its own job and cooperate with other agents to perform larger tasks [177]. An agent that is coded as a piece of software can have its own "intelligent" algorithm to solve local problems and perform local optimisation [178]. Multi-agent applications are very well suited to complex systems with a high ratio of disturbances. Problems can be solved locally with minimum influence on the whole system [179].

The important advantage of multi-agent systems when seen from the point of view of building integrated monitoring is the possibility of dynamic management of the system [180]. Agents can be added and removed from the system without switching its operation. This allows for easy reconfiguration of the system by adding new modules, functions, or tasks, and allows for the building of flexible, intelligent distributed systems [181]. The multi-agent philosophy is very well suited for building shop floor control systems for manufacturing [182]. There is considerable research in this area [27, 182–187]. Usually, these systems have a relatively simple monitoring module to control the status of the machine and process. An interesting research area is application of agent technology for optimization, mostly into system description and simulation [188]. Most multi-agent systems are based on special multi-agent platforms that allow for easy creation of agents, their management, and standardised communication. An example of this is the Java Development Framework (JADE) [189]. This follows standards developed and recommended by The Foundation of Intelligent Physical Agents (FIPA), which is a Standards Committee of the IEEE Computer Society [190] (Fig. 12).

The main advantage of multi-agent systems from the perspective of building complex integrated monitoring and supervision systems includes easy implementation of various intelligent algorithms, easy reconfiguration of the system by adding or removing agents or algorithms, and easy implementation of robust distributed solutions [178]. The simple modularisation of systems based on multi-agent philosophy is also key. This allows for the building of systems based on
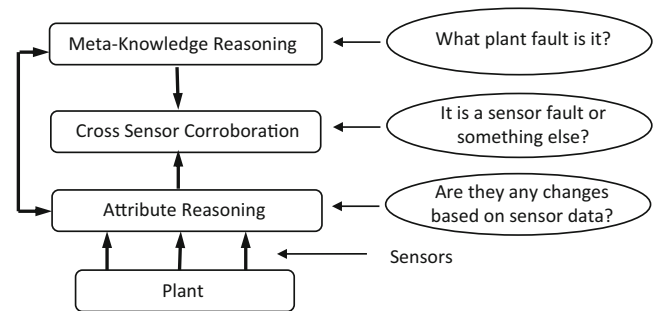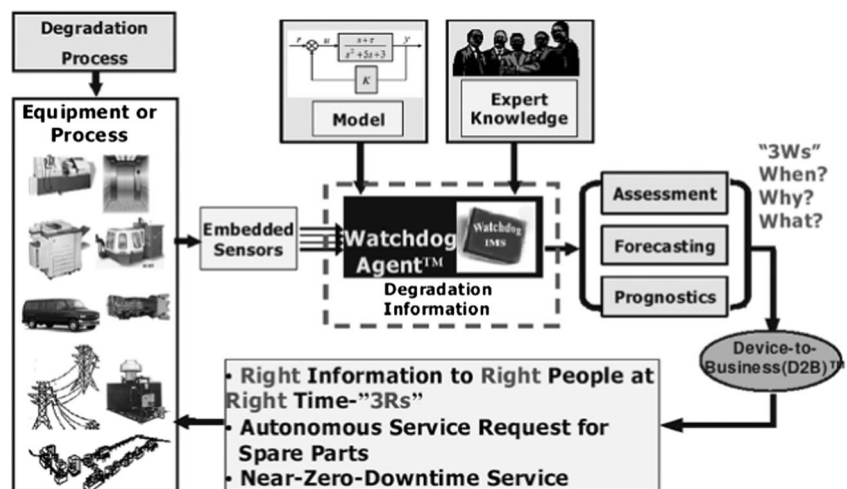

Fig. 13 Logical structure of COndition Monitoring Multi Agent System (COMMAS) [193]

standardised modules that will allow for significant reduction of development and implementation cost [192].

5.4.4 Application of multi-agent systems in monitoring

Multi-agent technology is especially interesting for building integrated advanced monitoring systems. The implementation of a multi-agent philosophy would allow for development of complex, intelligent, distributed applications connecting various monitoring devices to one system [23]. Multi-agent applications for manufacturing systems usually focus on shop floor control with limited monitoring functions. An example is "Operator 2.0" system that is based on multi-agent philosophy and IEC 62264 specifying control systems architecture [164] (Fig. 13).

Quite a bit of research has focused on the development of multi-agent based systems for maintenance in the process and power industry. In this sector, data acquisition is relatively simple, but the problem is geographical dispersion. The COndition Monitoring Multi Agent System (COMMAS) is one of the most developed multi-agent systems in this area and, importantly, has been implemented in practise [46].

This system is based on a three-layer architecture divided into an attribute reasoning agent (ARA), cross-sensor corroboration agents (CSCA), and metaknowledge reasoning agents

Fig. 12 Example of intelligent agent-based monitoring and maintenance system [191]

(MKRA) [193]. The ARA layer agents are connected directly to sensors and notice deviations in signals. The CSCA layer analyses information from the ARA, verifies that sensors are working correctly, check for possible failure, and tries to find reasons for abnormal signal levels. The MKRA layer is an inference engine that has an overall view of the whole system and evaluates the state of the plant base on information from the ARA and CSCA layers. The COMMAS system was developed over several years, and was finally implemented in the ZEUS Agent Building Toolkit [194]. COMMAS was implemented to monitor a gas turbine start-up sequence and to identify partial discharge signals emanating from defects in extra high-voltage gas insulated switchgear (GIS) at power substations [195].

The system was further implemented to monitor high power transformers. It was developed to monitor equipment at
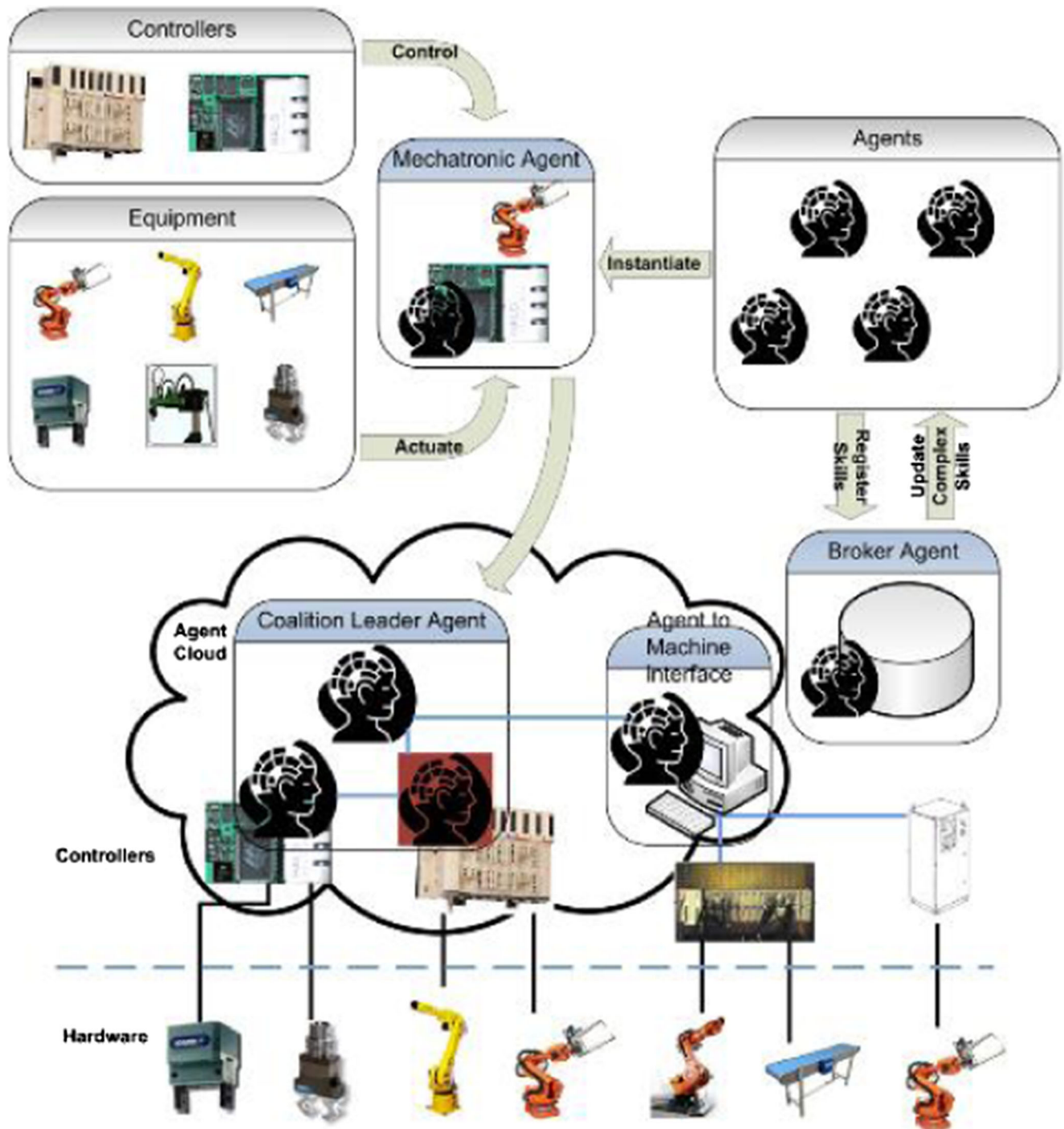

Fig. 14 Model of agent-based model manufacturing control system—a vision of a new distributed, intelligent production paradigm [32]

different locations and to use a number of condition-monitoring techniques [196]. Described systems were developed for the process industry where monitoring is relatively simple in comparison to machining processes, like cutting or milling. However, it shows the potential of multi-agent technology for building integrated monitoring systems dedicated to a machining process (Fig. 14).

5.4.5 Integration based on multi-agent systems—research direction

Applying multi-agent technology to integration of monitoring in machining systems is a major challenge that has not yet been well addressed. There are only a few publications in this area. Most are focused on solving particular problems important for building complex systems. An example is a multi-agent framework based on smart sensors and actuators developed for machine tool control and monitoring [147]. Another paper addresses the need for modular component-based diagnosis frameworks for modular manufacturing systems. A multi-agent distributed diagnostic framework operating based on a Bayesian algorithm was also proposed [197]. An attempt to build agent-based interaction-oriented shop floor systems to support emergent diagnosis is another example [198].

Multi-agent systems have a significant number of advantages important for IT systems used for manufacturing. Systems based on a multi-agent philosophy have been researched for almost two decades. During that time, many special toolkits have been developed to support application development. A number of systems have been implemented in various production companies, and also in the area of maintenance and monitoring in the process industry. As such, the time is ripe for the development of integrated advanced multi-agent monitoring systems for manufacturing systems, and for the machining industry as well.

of various IT systems. Integrated systems can now be configured according to current needs, for example in the frame of a supply chain or a product development network. At the same time, however, currently there is no possibility to exchange information between various advanced monitoring systems. Moreover, the building of a companywide monitoring system that facilitates a synergy effect to support production and to collect a history of parts production is very difficult.

This research review shows the potential areas for advanced integrated monitoring systems development. The analysis indicates several development directions that include sensors, CNC systems, new approaches in communication standards, and software solutions. The new direction based on multi-agent systems is very promising. There has been significant research and industrial implementation of monitoring and maintenance in process industry, the chemical industry, and power energy systems. The experience in developing these systems forms a base for the integration of advanced monitoring of the machining process. The direction forward will have to combine advanced tools, machine, and workpiece condition monitoring, maintenance functions, processes, and product history archiving. Systems will have to be integrated with advanced IT systems operating at both the management and supply chain level, and will thus likely be based on cloud computing.

6 Conclusions

Advanced monitoring systems developed for the monitoring of the manufacturing process should allow for efficient support of complex-product machining. Machine and tool condition monitoring enables the detection of most problems and allows for high accuracy in machining and high availability for machines. However, as shown in the latest literature reviews, there is shortfall in IT solutions that can effectively handle complex and advanced monitoring systems that would integrate various monitoring and supervision applications into one system. Integration of information flows about a company and production at the management level is a standard for almost all contemporary companies. New IT solutions based on Internet and cloud computing allow for easier integration

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