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Technologies for Cost Effective Automation in Manufacturing (Low Cost Automation)

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Abstract

At a first glance low cost automation could be regarded as cheap hardware (sensors, actuators and controller). That is of course an important point to consider. But today we are looking for a cost effective life cycle of an automation system: design, production, operation, maintenance, refitting or recycling, and human skill is also an important factor. Despite relative expensive components the complete automation system can be cheap with respect to operation and maintenance. As examples are discussed numerical controls of machine tools embedded in a work organization with a flat hierarchy; shop floor control with distributed information processing and decentralized decision making supported by software agents; PLC Systems, shifting from PLC´s to general purpose PC; Virtual PLC/Simulation as a means to optimize the layout of production systems with respect to cost effective operation and maintenance; Retrofitting of automation systems; smart devices, i.e. information processing integrated in sensors and actuators; net technologies supporting distributed manufacturing and maintenance. In conclusion, future perspectives for developments in virtual machining and wireless connected components are considered. Low Cost Automation is a cross sectional area benefiting from methodologies and developments of other fields of automatic control.

1. INTRODUCTION

Low Cost Automation promotes cost effective reference architectures and development approaches for production and transportation that properly integrates human skill and technical solutions, includes shop floor production support and decentralized process control strategies, addresses automation integrated with information processing as well as automation of non-sophisticated and easily handled operations for productive maintenance.

Low Cost Automation is not an oxymoron like military intelligence or jumbo shrimps. It opposes the rising cost of sophisticated automation and propagates the use of innovative and intelligent solutions at affordable cost. The concept can be regarded as a collection of methodologies aiming at exploiting tolerance for imprecision or uncertainties to achieve tractability, robustness and in the end low cost solutions. Mathematically elegant design of automation systems are often not feasible because of neglecting the real world problems, i.e. they are failure-prone and therefore often very expensive for their users.

Low Cost Automation does not mean basic or poor performance control. The design of automation systems considers its life cycle with respect to cost: **cost oriented automation**. Batch processing in manufacturing with decreasing lots, but increasing part complexity as well as mixed parts to be manufactured, demands for intelligent automation integrated with human capabilities of experience and knowledge regarding shop floor control and maintenance to save cost: **cost effective automation**. Soloman (1996) points to shortening product life cycles that need more intelligent, faster and adaptable assembly and manufacturing processes with reduced set-up, reconfiguration and maintenance time. Machine vision, despite partly of costly components, properly applied can reduce manufacturing cost (Lange & Hirzinger, 2002). In order to survive in a competitive market it is essential that manufactures have the capability to deploy rapidly affordable automation with minimum downtime. This capability to adapt to a changing manufacturing environment results in cost saving and increased production. The concept of low cost automation or **affordable** automation is the provision of the human mind (Soloman, 1996).

The reliability of low cost automation is independent on the grade of automation, i.e. to cover all possible circumstances in its field of application. Often it is more suitable to reduce the grade and involve human experiences and capabilities to gap the bridge between theoretical findings and practical requirements. On the other hand, theoretical findings in control theory and practice foster intelligent solutions with respect to saving costs. Anyway, reliability is a must of all automation systems, but this requirement has no one-to-one relation to cost.

As an example one may consider Computer Integrated Manufacturing (CIM). The original concept connected the design of parts automatically to the machines at the workshop via shop floor planning and scheduling software, thereby using a lot of costly components and instruments. After a while this kind of automation turned out to be very costly, because of a centralized control had to fight against uncertainties and unexpected events. A decentralization of the control and the involvement of human experience and knowledge along the added value chain of the production process required less sophisticated hard- and software and reduced the manufacturing cost and got CIM to its breakthrough even in small and medium sized enterprises (SMEs).

Low cost automation concerns also the implementation of an automation system. This should be as easy as possible and besides facilitate the maintenance. Maintenance is very often the crucial point and an important cost-factor to be considered. A standardization of components of automation systems could also be very helpful to reduce cost, because it fosters the usability, the distribution and innovation in new applications, i.e. fieldbus technology in manufacturing and building automation.

Low Cost Automation as a cross-sectional field in automatic control mostly not develops new control concepts but uses combinations of it and an integration of information technology.

2. SHOP FLOOR ORIENTED TECHNOLOGIES FOR MANUFACTURING

A recent study of the Fraunhofer Institute for Systems and Innovation Research ISI (Lay, 2002) reveals that booming revenues for automation technology vendors hide the fact that belief in automation in the German investment goods industry is giving way to sober realism. More than a third of 1000 reviewed enterprises had already reduced their degree of production automation or plan to do so. The most important reason: The insufficient flexibility of highly automated systems. The combination of losses resulting from conversion, idle time and high technical maintenance costs quickly negated the expected economic benefits. Today at many locations highly automated production facilities are making way for systems with significantly lower degrees of automation. Exaggerated automation was found just as often at small enterprises as it was at larger companies. Highly automated material flow systems in assembly and highly automated processing machines are partly seen as poor investments. Two thirds of unsatisfied companies indicated that today's shrinking series sizes can no longer be handled economically with these systems. Inadequate flexibility in capacities follows as the second most popular reason for dissatisfaction. Companies with innovative product ranges face special difficulties. They have considerable problems for assembly stations and material flows in production. It appears that short innovation cycles define the limits of economical automation.

The customer tries to get rid of old and costly systems and demands for cost-effective, simple and reliable systems, scalable and capable of stepwise improvement; distributed intelligence in networks and efficiently programmable systems.

Within the last years so called shop floor oriented technologies got developed (Erbe,1996) and achieved success at least but not only in Small and Medium sized Enterprises (SMEs). They are focused to agile manufacturing, that means to use an intelligent automation combined with human skills and experiences at the shop floor. With shop floor oriented production support human skills and automation create synergetic effects. The mastery of the manufacturing process is in the hands and brains of skilled workers at the shop floor. Automation gives the necessary support to execute tasks and rationalize decisions. This represents a strand of low cost automation. To run the manufacturing process effectively is not only a question of technology, though an essential one. Together with an adequate work organization wherein human skills can be developing themselves it establishes the frame for a cost-effective, competitive manufacturing in SMEs.

Recent achievements for manufacturing are:

- low cost numerical controls for machine tools and manufacturing systems (so called job- shop controls).
- Programmable Logic Controller (PLC) shifting from PLC´s to general purpose Personal Computers. PC´s can easily perform many of the functions originally built into a PLC.
- Life Cycle Assessment of manufacturing systems: design, production, implementation, maintenance, qualifying operators (human skill), refitting, recycling/disassembling with respect to costs.
- Information-/Communication-Technology integrated in manufacturing system components to foster an agile automation in networked manufacturing enterprises and their extension to virtual enterprises.

Low Cost Automation is also related to:

- Organizational change and implemented information technology in Small and Medium Sized Enterprises for cost effective use of automation/control systems;
- Total Productive Maintenance with Tele-diagnostic via Internet to reduce costs for specialists;
- The internet protocol; it can be used for networking of controls, sensors and actuators;
- Shop floor control and maintenance with decision support based on automatic generated proposals by multi agents.

Some criteria for shop floor oriented technologies are:
1) with respect to the man-machine interfaces:
- flexible machine tools with easy access to the working area
- manual and numerical controllable machine tools
- graphical-interactive programmable NC-controls as well as PC-software
- multimedia supported interpretation of the machine diagnosis respecting maintenance through operators,

2) with respect to machine-machine interfaces:
- PC´s at the shop floor with NC-programming software for different controls but with identical structures and user surfaces as these machine tool controls and with program transfer between machine controls and PC in both directions,

3) with respect to fine planning
- electronic planning boards or shop floor control systems usable by skilled workers for making decisions with respect to scheduling tasks, shorten the through-put time and solving problems caused by standstill of machines, missing tools or jigs and fixtures, material or personnel.

Group- or Teamwork supporting technology is an additional criteria. This means the technology should be usable in a sporadic manner by all skilled workers depending on their tasks just now.
The following chapters present developments and applications for a cost effective automation in manufacturing.

2.1. CONTROLS OF MACHINE TOOLS

Machine tools have a key position in manufacturing. The functionality, attractiveness and acceptance are determined by the efficiency of their control systems. The typical control tasks can be divided in the numerical controller, the programmable logic control, the drives and auxiliary equipment. Manufacturer of numerical control systems (computer numerical control/CNC) increase the effort for developing new concepts permitting flexible control functions with a broad scope of freedom to adapt the functions to the specific requirements of the application planned to increase the use of standardized components. This simplifies the integration of CNC of different manufactures into the same workshop environment. Even until today CNC are mainly offered as closed manufacturer-specific solutions and some machine tool builders develop their own, sometimes sophisticated controls. This keeps the shop floor inflexible, but flexibility is just needed by small and medium sized enterprises. Last time there is a growing tendency to use industrial or personal computers as low cost controllers in CNC technology, with a NC core on a card module, but connected to standard operation systems like Windows 9x or Windows NT. As PC hardware is easy available and under constant development, CNC based on it benefits from the technological advances in this field.

One of the low cost applications of these kind of CNC is called "job shop control" (http://www.ad.siemens.de/jobshop; http://www.hurco.com/products/DynaPath/).

Machine tools with job shop controls can be operated manual and if needed or appropriate with software support. This is an intelligent support enabling the switch in process from manual to numerical support. These controls are suitable for job shops with small lots and are easy to handle manual (conventional turning or milling) or programmable with interactive graphic support. Therefore the knowledge and experience of skilled workers can be challenged and a dividing of work in programming and operating is unnecessary, saving costs while avoiding organizational effort and is more flexible. Job shop controls with PC-operation systems can be integrated in an enterprise network with TCP/IP protocol. These allows for a flexible manufacturing, because not only an easy programming at the machines but also archiving of programs and loading of programs from other places is easy possible. Moreover the connection to tool data management systems allows for a quick search and ordering the right tool at the workplace. Figure 1 demonstrates the range of job shop controls with respect to lot size and productivity.

The main point for reducing costs and enhancing flexibility is based on PCs as controllers for machine tools. As said before, PCs are easy available, the performance

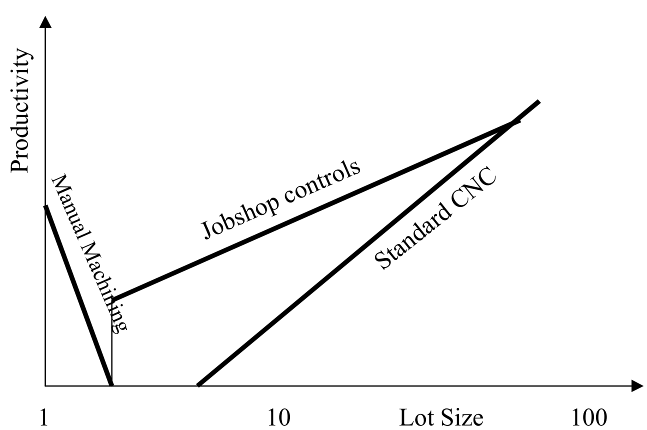


Fig. 1. Benefits in Productivity with Jobshop Controls; DynaPath control at a lathe

will be steadily improved and PCs are easy connectable, based on their operation system, to other components stand alone or in networks. Some industrial machine tool controls use a NC-kernel and only the interface to the outer world is PC-based. The Siemens

control 840 Di is fully PC-based, running on Windows NT. Another very important point for reducing costs at least in the long term is the using of open source software like LINUX. The source of this operation software is free available and therefore adaptable for customized solutions. Of course that is not always of advantage, when standardized solutions are easy available.
To enhance the precision and fault-tolerance of manufacturing processes as well as the flexibility of machine tools measurement systems, sensors for the (tele-)diagnose and adaptive grippers for handling and clamping of parts are added. To connect these components for reducing scrap and standstill of machines and thereby reducing manufacturing costs, open systems are necessary. The machine control as the central component should be combinable with different interfaces allowing for selecting sensors, actuators and measurement systems based on their desired functionality and not hampered by sophisticated interface problems.

2.2. Shop Floor Control and Decision Support

Shop floor control is the link between the planning and administrative section of an enterprise and the actual manufacturing process at the shop floor and is the information backbone to the entire production process. What at least Small and Medium Sized Enterprises (SMEs) need are low cost shop floor control devices, not only to avoid more or less complicated and expensive technology, but to effectively use the skill and experience of the workforce. The shop floor needs software support to enhance the flexibility and productivity. But support is to be stressed, not determination what to do

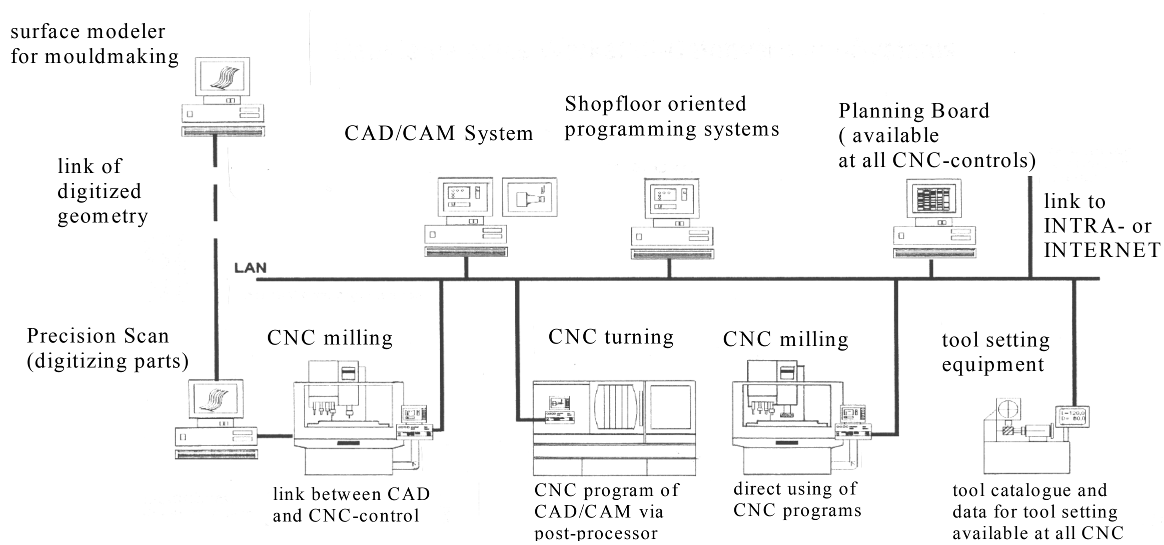
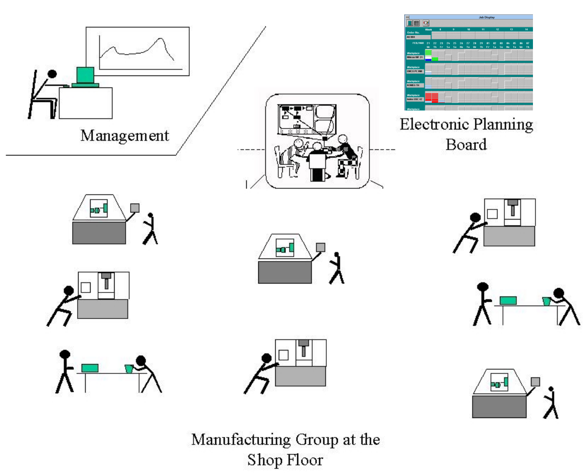


Fig. 2. Modules of a Shop Floor Network

by automatic decision of certain algorithm.

In small batch or single production (moulds, tools, spare parts) devices for a dynamic planning are desired. Checking all solutions to the problems arising at the shop floor, while taking into account all relevant restrictions, short term scheduling outside the shop floor either by manual or automatic means is not very effective. It is without sense to schedule the manufacturing processes exactly for weeks ahead. But devices that are capable of calculating time corridors are of advantage. The shop floor can do the fine-planning with respect to actual circumstances much better then the central planning. Human experience regarding solutions, changing parameters and interdependencies is the very basis of shop floor decisions and needs to be supported rather than replaced.

Figure 2 shows a network system linking all relevant modules to be used by skilled workers. Apart from necessary devices as tool-setting and others an electronic planning board is integrated. The screen of the board is available at all CNC-controls to be used at least as an information on tasks to be done at certain workplaces to a certain schedule. As all skilled workers as a group are responsible for the manufacturing process they have beyond the access to information the task of fine-planning of orders they got with frame data from the management. They use electronic planning boards at the CNC-controls or alternatively at the PCs besides the machines.



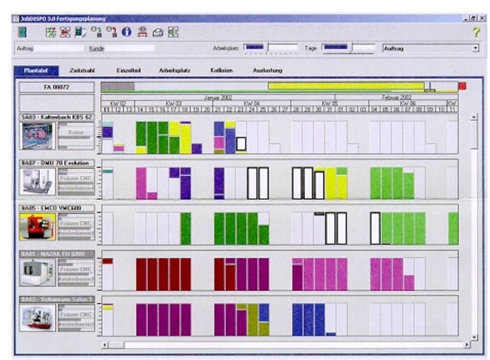


Fig. 3 and 4. Job Scheduling with an electronic planning board of Fauser AG

A planning and scheduling support with soft constraints was developed by (http://www. Fauser-ag.com) called JobDispo (Fig. 3). It consists mainly of an intelligent planning board with drag and drop technology of the graphic editor and a database SQL, running on PC´s under Windows 9x or NT. The operators in a manufacturing group get only rough data of orders from the central management. These data concern delivery time, material, required quality, supply parts, etc. Using the support the workers decide on the sequences of tasks to be done at the different places of the manufacturing system. The electronic planning board simulates the effects of their decisions. Normally more than one task needs the same resource at the same time. The operators are enabled to change the resource limits of work places and machines (working time, adding or changing shift-work, etc.) until the simulation results in acceptable work practice and fulfill the customer demands. If this cannot be achieved the central management has to be involved within in the decision. In SMEs manufacturing groups are empowered to regulate their tasks by themselves based on frame data of the management. JobDispo is partly automatic but allows for soft constraints to make use of the experiences of the human operators (Fig. 4).

As a future perspective for decision support devices or tools the research work of Sawaragi et al (2000, 2001) are mentioned. His group introduced an interface agent as a associate for human operators, preventing them from a flood of data for decision making and on the other hand avoiding computer based instructions for taking action. According to Sawaragi an interface agent is a semi-intelligent software that can learn by continuously "looking over the shoulder" of the operators as they are performing actions. The agent has to coexist with the operators so that it can evolve by itself as the operators proficient level improves, but in a way to stimulate the operators creativeness, rather than to replace them by itself after some time. To be a human collaborative an interface

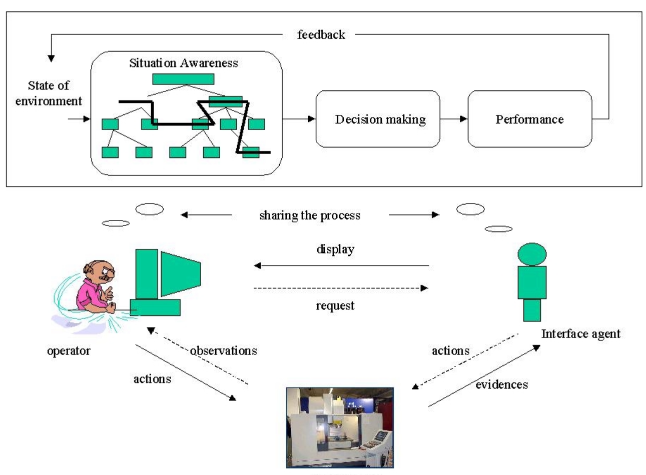


Fig. 5. An interface agent as an associate for a human operator (after Sarawagi, et al, 2000, modified)

agent has to make decisions analogous to humans. Sawaragi proposes a shift from classical normative decision making to a naturalistic decision making concentrating on the proficient experts situation assessment ability looking at a situation and quickly interpreting it, using their highly organized base of knowledge recognizing and appropriately classify a situation. Sawaragi calls this style of decision making a recognition-primed decision (RPD-model after Klein et al, 1993). He proposes this model for developing an interface agent capable of flexibly organize the appropriate appearance of the status of the manufacturing system (or plant) discriminating among what is now relevant and what is not for assisting the operators "situation awareness". A taxonomy of possible faults are organized in a hierarchical order (fault-tree method) and a hypothesis on plausible faults can be defined with connecting tree-nodes (or leaves) of different levels, called "conceptual cover". This is to avoid the lengthy way through a lot of nodes not relevant to solve the problem. Human operators use different conceptual covers based on the situation and their experiences. Effective ones will be identified by the interface agent and stored as experiences for exchange with the operators (Figure 5).

Again we are focusing on a support for human operators with software agents for job-shop scheduling rather than an automatic decision. A manufacturing system is a net of different machine tools and handling devices. It processes information and material. It have to be operated to achieve an optimum with respect to material and time resources regarding the tasks to be done. This represents the normal work practice and may be defined as normal job-shop scheduling. Many attempts have been done to solve this combinatorial problem, like CSP (Constraint Satisfaction Problem). An overview and discussion give Dimopoulos&Zalzala, 2000). But static scheduling problems are not mapping the real world practice. Additional express orders or just not available resources causes a fluctuation around this normal work practice or performance of the manufacturing system. Inappropriate planning and control caused by time and costs pressure, tight resources on personal, or deficiencies by illness, all unexpected issues are moving the system to the limit of the space of acceptable performance. This can occur unnoticed and will be perceived only when the quality decreases, times of delivery are exceeded or through put time increases. A decision support has to intercept such movements of the normal work performance against the limit of acceptable performance. Attempts have been made to formulate these problems as Dynamic Scheduling, using machine learning methods or extensions of CSP discussed also by Dimopoulos&Zalzala (2000). But all these attempts are not satisfactory respecting computation time and probably cannot take into account all possible uncertainties.

2.3. Life Cycle of Manufacturing systems/ Cost of Ownership

To reduce the Life Cycle Costs or Cost of Ownership of an automation system becomes an important task within the subject of Low Cost Automation. The whole chain from

design, production, implementation, operating, maintenance and reconfiguration or retrofitting to recycling comes into consideration. For instance, some components of a system could be expensive if the reconfiguration- or maintenance-costs will be reduced. Meanwhile software and internet connections to the machine tool builders are available that make the total cost of ownership and life cycle costs transparent to the management of an enterprise. It is enabled to regularly check the state of the machines by using such a service and transferring up-to-date performance data to the manufacturer. The manufacturer then carries out a data evaluation in order to deduce the availability of the system. This evaluation is passed on to the user through any given communication form, i.e. e-mail, fax, text message or voice mail. Thus the customer receives an immediate statement about the expected availability of the machine for the next production shift.
The customer transfers information to the manufacturer, which will be further evaluated. The necessary maintenance work is then determined and entered as a suggestion to the To-Do-List of the machine's Online-Service-Logbook. The customer can call up this information at any time in order to receive input for the planning of maintenance work.
After completion, the maintenance work is then reported to the online maintenance assistant. Thus the basis for consistent life-long documentation of the machine is established. It is a win-win situation for all those participating in the previously described scenario. The enterprise takes part in the machine builders know-how of the system and receives for its production plans a short-term prediction about the availability of the machine tools. The machine builder is also capable of collecting data about the actual usage profile of the machines. In this way, it is possible to adjust the offer to better match the needs of the customer enterprise.
Within the previous scenario, the transfer of machine data plays an essential role. During this process, security precautions must be taken in order to prevent any unauthorized access to such information. More important, all production secrets have to remain within the enterprise production system. At the end of a service session, the enterprise receives a report of the session. The account for the services rendered is then calculated according to any given variety of pay scales. All of these steps require qualities like availability, dependability, information protection and confidentiality. A more detailed description and consideration can be found at http://www.e-industrial-services.de.
Another development focuses on a systematic fault clearance, that makes run again the core value-adding processes of a manufacturer – the production processes. The software serves a machine or plant through all its lifetime: system development and construction, ramp-up, operation and to some degree at system change. The throughout collected data allow many value-added services like a systematic fault clearance, reduction of faults or by an immediately back-flow of know-how an improvement of machinery (refinement). The complete historical data allow numerous applications and analysis. This finally

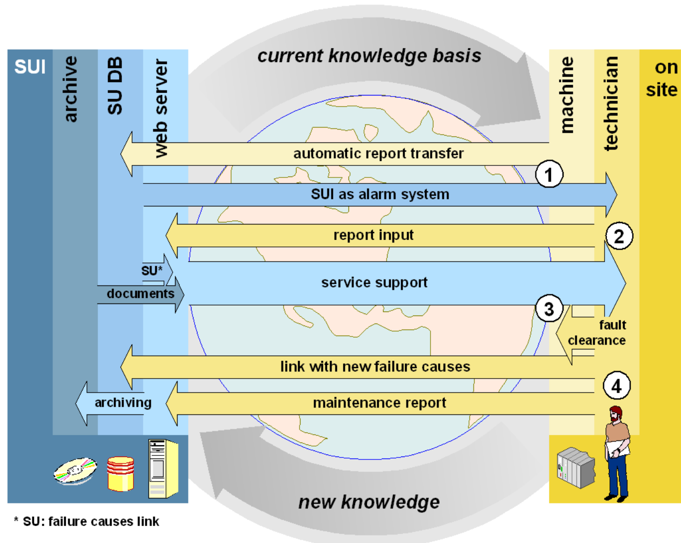


Fig. 6. Machine Lifecycle. SARA SUI application covers essential parts of a machine‘s lifetime (Kögel, 2002).

reduces lifecycle costs and may be interpreted as a win-win-situation for both, service client and service provider (the machine builder). A Manufacturing Execution System (MES) deliver information enabling the optimization of production activities from order launch to finished goods. Using current and accurate data, MES guides, initiates, responds to, and reports on plant activities as they occur. This drives all effective plant operations and processes. It focuses on the shop floor which is the place with the most deficits – and of course of all the value-adding processes of a company. The above mentioned environment of production is integrated by interfaces. The so called „Vertical Integration“ of Automation and IT is concentrated on problems of production and manufacturing. The Failure Analysis Information System SUI (Figure 6) focuses on the systematic fault clearance that is the basic task at a machinery during its lifetime (http://www.sara.de/).

The Total Cost of Ownership (TCO) and the Lifecycle Costs are transparent to the management. The benefits in machinery lifecycle support arises with a Service Information Management. This concerns either the machinery itself or the service environment:

- constantly high service quality
- cost savings – in service and operation
- service can be done more quick or can be done at all (instead of unsuccessful return)
- fewer visits of technical staff on site
- less downtime and therefore reduced operational costs

- data history of the complete lifecycle information allowing for numerous analysis, both for development/construction and at system change.

2.4. COST EFFECTIVE MAINTENANCE STRATEGIES

Maintenance should keep a systems facilities functioning in order to contribute to the enterprise target. So, maintenance should fulfil the right CRAMP parameters (Cost, Reliability, Availability, Maintainability, and Productivity) for any automation system. Maintenance strategies and operations are considered as a complete process aiming to maintain the production resources while inter-working with other shop floor and business processes (automation, planning, quality, management, financial) to carry out the global enterprise goal. Engineering of such a maintenance system needs a holistic approach for integrating views and evaluations, not only of the systems themselves, but also for their mutual interactions and their interactions with the environment (Morel, 2002).
After Morel two approaches can be considered respecting the knowledge required for the development of actions to maintain the service quality of the automation system:

an a posteriori approach based on an exploitation of the system data coming from experience and the knowledge practices of the real operation. It allows for decision making of maintenance strategies as a feedback in the system design phase or as an optimization on line.
Operating experience processing is the using of reliability engineering analysis, performed either at the beginning or during the life of an automation system to ensure the system will provide the intended functions, throughout the whole life. One of the methods most used to improve the maintenance plans for automation systems is RCM (Reliability Centered Maintenance). RCM is a procedure for determining maintenance strategies based on reliability techniques (Cotaina, et al., 1998). The methodology takes into account the prime objectives of a maintenance program:
- Minimize Costs
- Meet Safety and Environmental Goals
- Meet Operational Goals

The effects of redundancy, cost of spare parts, costs for maintenance personnel, equipment aging and repair times must be taken into account along with many other parameters. The RCM process may be used to develop a living strategy with the plant model being updated when new data is available or design changes take place.
Another good source of failure information on an automation system is the experience of operators on site. Translating this information into future probability of failures can be performed with the Bayesian reliability analysis (Morel, 2002).

an a priori approach based on the system knowledge to controlling system variables regularly, even continuous ones, for (a) optimizing the intervals between repairing, (b) reducing the number and the cost of unexpected standstills, (c) anticipating the failings of the system. Some studies on the efficiency of the management in maintenance showed that a big part of maintenance costs results from useless or badly made repairs. For example, sometimes scheduled maintenance is blind because the equipment, which is changed, could be in a perfect operating condition. This not only increases the cost of production, but also decreases the lifetime due to the damages of equipment done by the maintenance action itself. In addition a bad maintenance strategy has disastrous consequences on the product quality and therefore on the competitiveness of the enterprise. An implementing of condition-based and predictive maintenance substitutes scheduled maintenance to decrease expenses and to improve the global performances of the automation system. Studying the systems "degradation" to anticipate its failures offers an image of the future situation of the system. Moreover, the objective of the diagnosis process is to identify the components, which are responsible of the system degradation, in order to intervene and to restore only those components, which are degraded, or failing.
Therefore the implementation of these processes within the framework of a predictive versus pro-active maintenance strategy involves some a priori knowledge on the system and on its components with a use of this knowledge to represent the views on the future directions of the system (Morel, 2002).

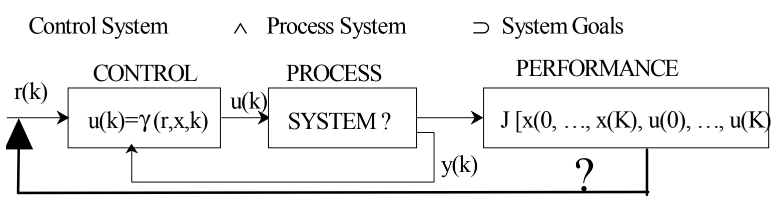


Fig. 7. A closed-loop system with system performance optimization rather than control performance optimization (Morel et al (2001)

Morel stresses the consideration of the performance of the complete system, that is interesting the owner respecting the cost, rather than the control performance only; i.e. a compromise between cost of maintenance and cost of standstill of the automation system has to be find (Figure 7). Due to increased demands on performance of manufacturing systems (quality, reliability and safety) spending on maintenance is likely to grow. Therefore an agility for the maintenance of the next generation of information- intensive

manufacturing systems requires to broaden the mindset of the well-established system-oriented approaches in favor of more intelligent technologies and way of thinking.
After this more theoretical considerations some operational solutions of maintenance are now discussed. The concept of Total Productive Maintenance (TPM) integrates maintenance into production and therefore enlarge the tasks of the productive workers at the shop floor. To master these additional tasks the operators of manufacturing systems need a deep understanding of the structure and support for their decision making respecting active and proactive maintenance. Necessary for these tasks are well prepared interpretations of the diagnosis information. With this support and their collected experiences when operating the manufacturing system they are enabled to locate the problem and to decide if it is possible to solve the problem by themselves cooperating in a group or a specialist have to be consulted. With this support and their experience when running the system total productive maintenance will be effective for enhancing the availability of the systems.
Often expert systems are in use to instruct the operators to detect and to remove faults or repair parts of machines and manufacturing devices. But, if even experienced operators are sticking long time on advises of these systems their competence is fading away. They loose their understanding what happens and what to do. An alternative was developed by John & Timpe (2000) and Marzi & John (2002). Operators use the information provided through a multi agent support together with their experiences what to do to achieve again the normal operating state of the manufacturing system (Figure 8). Two software

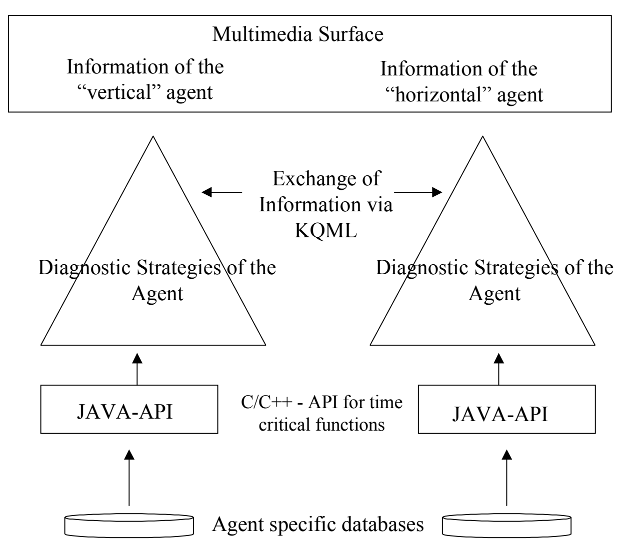


Fig. 8. Architecture of the software agent system (after John&Timpe, 2000)

agents are cooperating together and with the operators. A "horizontal agent" are looking for faults along the same level of a component-tree regarding the functional dependencies between the components. The component-tree represents a hierarchical order beginning with the machine itself until the smallest component. A "vertical agent" looks for faults in a component and its sub-components. Both agents use implemented specific strategies based on information of the machine builder and experiences of former problem solving. The effect of the interaction of both agents corresponds the conceptual cover introduced by Sawaragi (2000). Obtained experiences when running and maintaining the agent system can be fed back to the knowledge base (enhancing or altering the component-tree) thereby enhancing step by step the performance of the system. Also the diagnostic strategies can be enlarged or changed by the operators to make the system more effective and adaptable to new challenges. The support could also be used to point to approaching inadmissible system states for indicating the limit of the space of acceptable performance. This is possible with the help of a simulation tool that is not yet developed.

2.5. RETROFITTING/REMANUFACTURING

Economical aspects often require considerations how to enhance the productivity and flexibility of the manufacturing process to acceptable costs. The main points in this respect are work-organization and the used technology. Both have to be considered together because they affect each other. Investing in a new or at least better technology is connected to decisions for machines with enhanced productivity and also to producing a better quality the customers are willing to pay for. Considering machine tools or manufacturing cells or systems it is not always necessary to replace them completely. In many enterprises one can find conventional machines in a very good state but meanwhile not suitable to produce parts of high quality in an adequate time. Conventional machine tools like lathes or conventional milling machines have usually a machine bed of a good quality and stiffness. They should not be thrown on the scrap-heap. These machines could be equipped at least with electronic measurement devices as linear rules to improve the manufactured quality with respect to required tolerances. The next improvement could be the refitting with a numerical control. This certainly requires servo-drives for each controllable axis while the drive of the spindle will be controlled using a frequency converter. Numerical controlled machines of the first generation sometimes only need a new control to put them to today's standards, what is called "upgrading".

Sometimes it is desired to save the conventional handling of machines despite its retrofitting, i. e. moving the tables and saddles mechanical with hand wheels in addition to the numerical controlled servo drives. This facilitates the manufacturing of simple parts before using the advantages of a CNC-control to manufacture geometrical complex work pieces (see "job shop controls" in chapter 2.1). To save this conventional handling certain constructive measures are required and need to be considered early. Often it is

Fig. 9. Refitted milling machine tool

not necessary to replace the main drive, i. e. the motor of the milling spindle or mandrel of a lathe. A frequency converter enables to control the speed via the CNC- and logic control. One has to consider this cost-effective measure when planning the retrofitting. The interface between the numerical control and the servo-drives as well as other devices like frequency converters is the logic control (programmable logic control, PLC). Programming the logic control is one of the main tasks of the refitting process. As a side effect this gives the opportunity to train skilled workers and technicians in the maintenance of numerical controlled machines. The mode of operation „Diagnostic" enables to adapt the numerical control to the refitted conventional machine. Configuring of machine-parameters adjusts the precision and the dynamic quality. The knowledge and the experiences of the subject are inestimable for the later maintenance. Therefore, it is recommended to project the retrofitting to this part most carefully. More information on retrofitting can be found at web sites: http://www.machinemate.com and http://www.anb-industries.com. Figure 9 shows a retrofitted conventional machine tool to numerical control.

Retrofitting at the shop floor of an enterprise could be done with the employed personnel, eventually with support of external experience of appropriate service companies. This enhances the capability of the workforce to maintain automated machines and devices and reduces the expenses for service companies, reduces downtime of machines and thereby increases the availability (Nong Ye, 1994; Zimolong and Konradt, 1993). Production to market demands requires the high availability of machines and this is last but not least a problem of maintenance by skilled personnel.

2.6. VIRTUAL PROGRAMMABLE LOGIC CONTROLLERS

Production loss is a costly factor in all branches of manufacturing industries that occurs during the planning, programming and commissioning phases of manufacturing lines. In order to reduce production loss, a main aim is to perform as many tasks as possible in parallel to the running production. This is only made possible through accurate simulation.

Within manufacturing cells a large number of PLCs is used to control and to coordinate different components, to integrate sensors, actuators and to build the communication interface for connecting controller systems. The integration of PLCs into simulation systems enables to testing and optimizing the manufacturing cell without any danger,

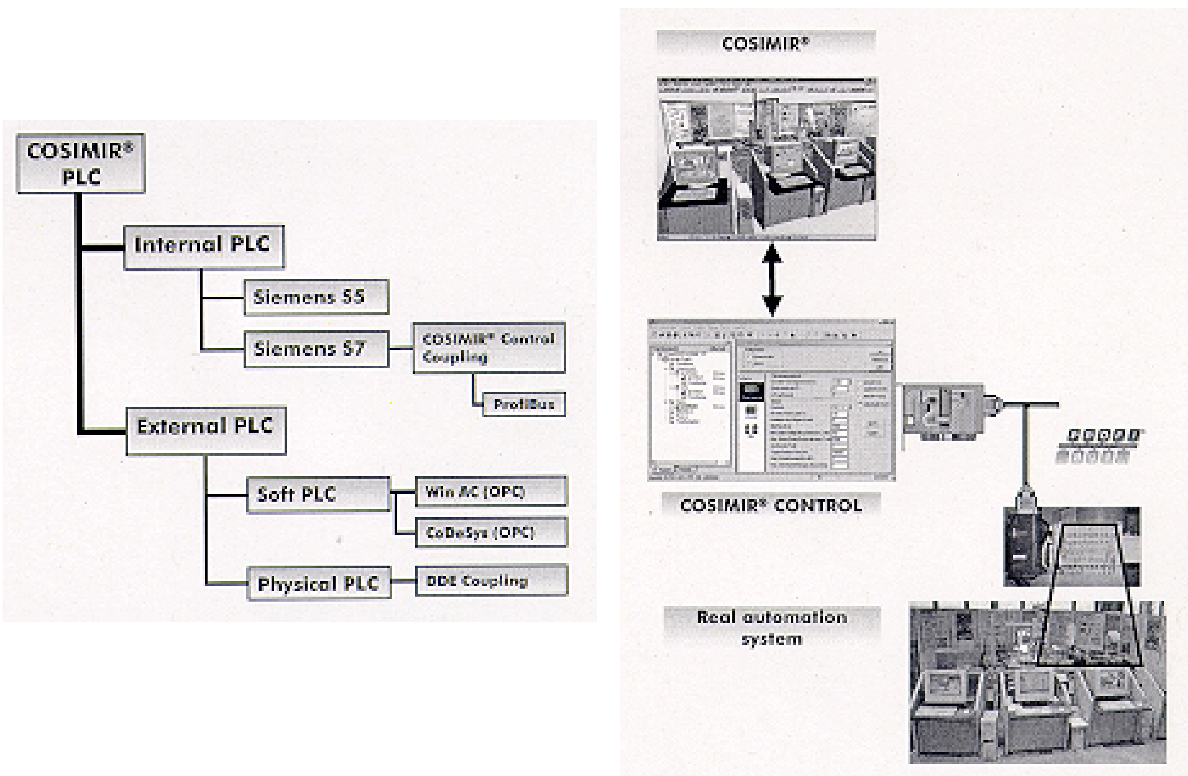


Fig. 10. PLC types supported and Connection to a physical PLC (Freund et al, 2002)

neither for the mechanical and electronic components nor for human operators. It is also possible to generate error situations without engaging the real cell. Freund et al (2002) developed a software system COSIMIR® running on PCs with Windows 9x (http://www.irf.de/cosimir.eng/industrial/). The system divides the range of simulated PLCs into internal and external PLCs. Internal means the usage of an interpreter integrated into the system. The algorithms of this software component minimizes the gap between simulation and reality. External means the simulation of PLCs of different manufacturers, i.e. integration of PLCs into the simulation and not to simulate them explicitly. An significant advantage of internal PLC simulation is the fact that no components from outside are necessary. The simulation is self contained and does not use any additional software licenses or hardware systems. The external PLC simulation benefits from the reliability of physical or Soft-PLCs. The method of connecting external components to the simulation system guaranties a high reproducibility of the simulation results in the real environment. The system is capable of elaborating PLC programs generated through the programming environment of the PLC manufactures. The program is loaded into the simulation system and the integrated PLC kernel executes it. No translators or post processors are necessary. After the simulation the PLC program can be downloaded directly into the physical PLC of the manufacturing cell without modifications (Figure 10). Both, simulated and real PLC programs are identical. The close coupling and the interchangeability of hardware and software components guarantees the transferability of simulation results to the physical automation system. The integrated fault simulation may be used for error handling as well as for training purposes in diagnostic. Moreover, during the operation and maintenance of an automation system its simulation models can be used to optimizing the process without interfering with the running manufacturing. It reduces or avoids downtimes for the reconfiguration or maintenance and therefore cost.

Now as the first integration of PLCs into simulators are available on the market, similar to early developments in robot controller simulation, a standard should be created similar to that for robot controllers, in order to create a market of compatible products, which would increase availability and reduce costs for simulation models. Such a standard is also required for compatibility with Virtual Robot Controllers. Incompatibilities and diverging concepts would otherwise lead to losses in simulation accuracy. For more information on Realistic Robot Simulation (RRS) see e.g. Bernhardt et al (2002).

2.7. ROBOTS IN MANUFACTURING

Robots can be divided in three classes (Whittaker, 1993):

1. Programmed robots perform predictable, invariant tasks according to pre-programmed instructions. They are the backbone of manufacturing, mostly pre-programmed off-line with a simulation of the programmed tasks before loaded to the robots at the shop floor (for a so called realistic robot simulation, see paragraph 2.6).

2. Tele-operated robots includes machines where all planning, perception and manipulation is controlled by humans. Also called manipulators, they are served in real-time by operators. Tele-operation over great distances is one of the challenges for these kind of robots (in minimal invasive chirurgy and distributed manufacturing).
3. Cognitive robots sense, model, plan and act to achieve goals without intervention by human supervisors. They serve themselves to real-time goals and conditions in the manner of Tele-operators but without human intervention. These are called Field Robots or autonomous robots.

As robot technology is mostly regarded as costly, one can see today an application not only in mass-production (automobile industry) but also in small and medium sized enterprises (SMEs), manufacturing small lots of complex parts. The rising product variety and customer pressure for short delivery times put robots in the focus. Hybrid forms of tele-operated and programmed robots are therefore attractive. The stationary application of such robots are not very useful due to the always changing needs in SMEs and specialists for installing and programming are expensive and hardly to find in SMEs. A Place&Play automation concept was developed to overcome these difficulties Fig. 11).

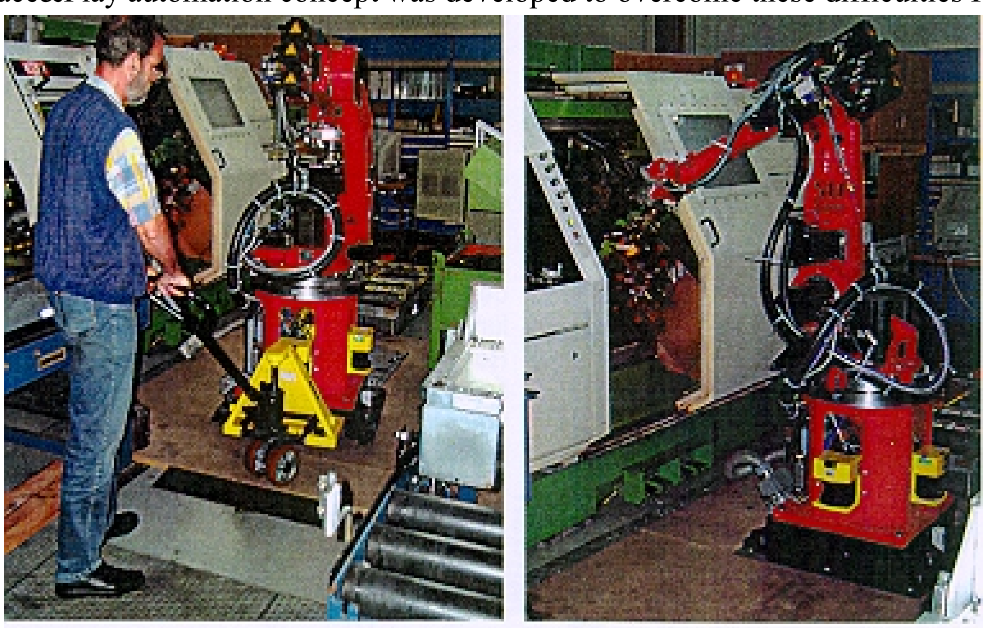


Fig. 11. Movable robot serving a manufacturing cell

(http://www.gfai.de/forschungsbereiche/robotik/index.htm). It consists of a moveable robot that can easily be put to its working position and set to use with a minimum effort. After moving to its place for serving a manufacturing cell, for example, a prepared interface

has to be connected to the cells controller. Sensors have been developed for securing the working area of the robot. The programming process is based on picking up the corresponding methods of the cell programming and is graphical-interactive for supporting the operators. This application of robot technology can be regarded as an affordable automation.
Even field robots are applicable with affordable cost. Ollero (2001) describes as an example (among other applications) an autonomous truck. It could be also an unmanned vehicle in a manufacturing site. According to Ollero low cost should be referred to the components to be used as to system design and maintenance. Sometimes a trade-off between general purpose components and components tailored to the application has to be considered. Given expensive components then the design of the field robot respecting modularity, simple assembly and the maintenance related to the reliability and fault detection properties are important for reducing cost regarding the life cycle.
An important point respecting the cost of robot technology in SMEs is the role of the human operators. Future teleoperators will combine robotic and manually controlled functions, with the degree of automation depending on the success of artificial intelligence research. While using advanced systems, human operators will carry out some varying mix of tasks (see http://www.ornl.gov/rpsd/humfac/hfessays.html)

2.8. NET TECHNOLOGIES

Computer technology as the basis of modern control systems continues to develop at a rapid pace. Users not always have the time to invest themselves and assess the pertinence of these new developments. However they expect effective solutions that are less expensive to implement and maintain. Moreover they expect flexible and open systems.
Internet technologies have swept over office systems and are now arriving to the manufacturing industry. It offers a high flexibility for managing information "and can offset the lack of an application layer in Ethernet-based local networks" (Laine, 2000). In his paper "Impact of Internet Technologies on Industrial Fieldbusses" Laine discusses the main directions of profound changes in control systems:

- decentralization of processing and cooperation between equipment of different types
- integration of intelligent equipment to meet the special needs of the application
- standardization and non-dedication of certain system components to increase openness.

The decentralization allows information to be processed at the proper level (see also chapter 2.9 on Smart Devices). Fieldbus have their prime qualities here respecting their speed in transmitting information, their reliability and their immunity to industrial disturbance. As a standardization of fieldbus technology lacks, one is confronted with a small number of solutions. Laine argues that even if a standardized net work were defined, the right profile would still have to be chosen. Therefore Laine mentioned some criteria to be to consider:

- cost, which must include all related costs, including cabling and maintenance accessories,
- solutions that match the need of the application in question, avoiding excessive and untimely generalizations. A theoretical throughput of 100 MB/s is not necessary when an effective throughput of 1 MB/s would be sufficient,
- consistency between different levels,
- effective performances in the system configuration chosen. For example, a 10 MB/s network may not be suitable because it cannot send the same data to several devices, whereas a network with a slower throughput can,
- the capacity to separate real-time and service traffic, in order to ensure service quality in both cases
- easy setup.

After some discussions on Ethernet with its mostly used protocol TCP/IP Laine demands for a coexistence of fieldbus and Ethernet, i.e. make fieldbus TCP/IP compatible. Fieldbus that can support TCP/IP in addition to their own stack would adapt to a broad dissemination of web technologies. Those technologies are in the process of completely changing business computing . Their advantages open interesting doors for industrial computing, by simplifying the integration of all tasks of decision making in management and shop floor of the enterprises. Indeed, this drives a cost effective automation. According to Laine "such tools will call into question the traditional organization of companies and the idea that an item of information belongs to a specific framework. Future systems applying the Fieldbus/Web combination will be able to offer the right information at the right place to the right person at the right time". A useful information fieldbus technology gives http://www.schneiderelectric.com/en/pdf//ect197.pdf

Tele-service and Tele-diagnostic offered by machine tool builders via the internet can reduce the downtime with improving the maintenance capability of the operators at the shop floor (see also chapters 2.3 and 2.4). Also the e-business of tool-catalogues, tool-management- and fixture-systems is possible with internet connection at or close to the machine tools reducing set-up time and therefore throughput time.

Further useful information on a "Transparent Factory" with respect to saving cost when organizing the data transfer between machine, equipment, shop floor planning not only for the individual but also networked enterprises are available from the web site of Schneider-Electric http://www.transparentfactory.com/

2.9. SMART DEVICES

Computer-based automation systems are quickly developing as a result of the development of digital technologies, which offers a favorable price ratio for computer components, while their reliability is steadily growing. This increase in the computational power meets the extension of automation goals which take into account not only control needs but also those of maintenance, technical management, quality management, supervision, etc.

These developments allow for computer-based automation system to evolve from centralized architectures to distributed ones. The first level of the distribution has been consisted in deporting inputs and outputs in order to reduce the wiring cost by using fieldbus as a communication support. The second level integrates data processing in module setting as near as possible to sensors and actuators. These smart sensors and actuators can communicate, self diagnose, or make decisions (M.K. Masten, 1997). One step to realize smart sensors is to add electronics “intelligence” for post processing of the outputs of conventional sensors prior to use by the control system. The same can be applied to actuators. Advantages are tighter tolerances, improved performances,

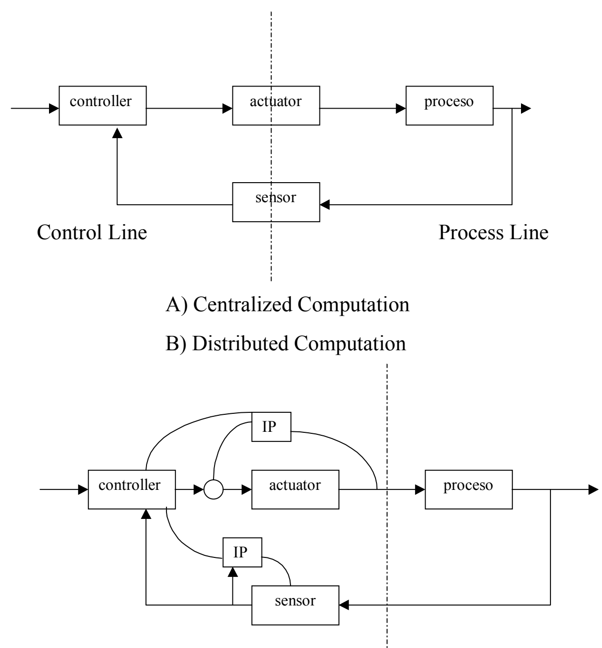


Fig. 12. Basic Control Loop (Albertos, 1998, 2000)

automatic actuator calibration, etc.

In the upper part of Figure 12 (Albertos, 1998, 2000) a sensor is considered as a transducer, converting the measured variable into another one, easier to handle. The

control line mainly performs an information processing delivering the manipulated variable converted from the control action. The actuator manipulates the process input variable. The lower part in Figure 12 shows a distributed computation structure. The sensor and the actuator involves a number of information processing enhancing the performance and Albertos points to a shifting of the division between process and control from left to right. According to these evolutions, the manufacturer of devices has to be able to conceiving and distributing products that are well adapted to the particular application. However for the sensors (or actuators) manufacturers, the design of intelligent devices is quite difficult according to the variety of fieldbus, and the needs of flexibility and standardization. In that sense, a development tool for design smart devices has been conceived. This tool allows for easy realizing the software for an application, that can be implemented in a micro-controller in order to obtain smart devices (Bayart, 2001).
In general, the organization of the intelligent part of an instrument contains:

- a module, which takes into account the local physical, inputs and outputs
- a module which has in charge the communication variables
- and a microcomputer which contains a central processing unit which performs the specific functions and memory modules.

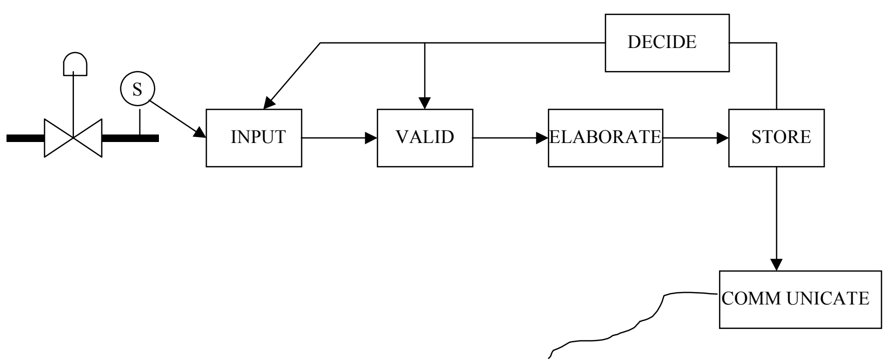


Fig. 13. Layout of a smart sensor (Starosviecki, Bayart, 1996)

After (Starosviecki, Bayart, 1996) the smart sensor activities are (Fig. 13):
- INPUT: the information is gathered from the process
- VALIDATE: based on internal or complementary measurements
- ELABORATE: a modified variable is computed
- STORE: the result is internally stored
- DECIDE: a selection procedure among different options takes place

- Deliver: the data are transferred to the COMMUNICATION channels to the required device: data base, control algorithm, operator,..

A smart actuator follows more or less the same structure.

3. Future Perspective

Virtual machining could be an important tool reducing cost in manufacturing. Skilled workers could use this tool to plan the complex manufacturing for optimizing in short time. Furthermore a change of the production process due to customer demands can be quickly simulated to find the optimal way. Virtual tools are available using tool management systems provided by tool makers via the internet. An accurate simulation of jigs and fixtures is also possible using data of fixture suppliers via the internet. The workers can document the first assembly of fixtures in a machining center in a data base at a PC or the machine control using a digital camera. This allows for saving the knowledge and experience for future use and shorts the setup time when manufacturing new parts.
The today offered NC-simulation software is not realistic in the sense of the Realistic Robot Simulation (see chapter 2.6). The offered software of different companies is at the most based on data generated of postprocessors of the respective numerical control. But the complete control should be simulated. A realistic simulation of a manufacturing process in a machining center by high-end visualization are under development .

Powerline Communication (PLC) is a new technology that sends data through existing electric cables alongside electrical current to turn the largest existing network in the world, the electricity distribution grid, into a data transmission network. The benefits are

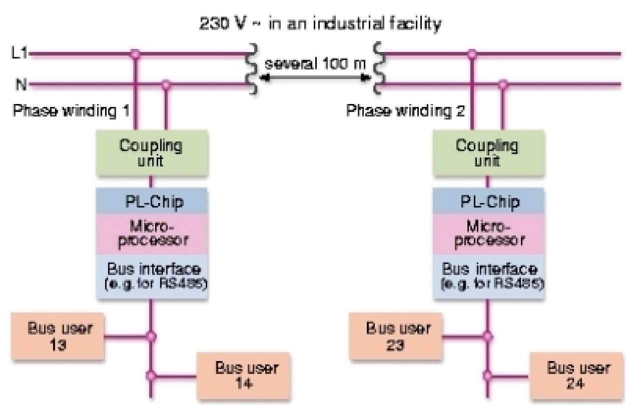


Fig. 14. Powerline Communication network (Siemens AG)

obvious: valuable additional uses without the need for expensive infrastructure investments (Fig. 14 and 15). PLC could be a candidate for low cost solutions in factory automation avoiding additional wiring. The Internet and the explosive growth in the number of its users are also helping to make it both feasible and inexpensive to provide not only electricity but also high-speed data services—an important edge on the competition for just about every local power company. In itself the idea is not new. For decades, very simple signals such as "on" or "off" commands for street lighting—have been transmitted via the power grid. But only since the development of complex

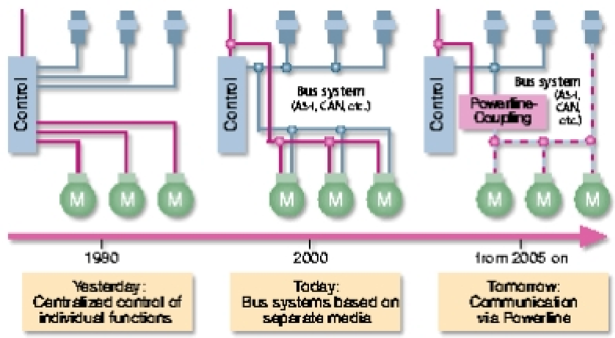


Fig. 15. Powerline Communication, expected forthcoming development (Siemens AG)

frequency modulation processes such as OFDM (Orthogonal Frequency Division Multiplexing) together with highly integrated and inexpensive semi-conductor chips, have data transmission rates of 1Mbps and more been possible (1 Mbps = 1 million bits per second—16 times faster than ISDN). PLC becomes attractive to purchasers of new facilities or equipment if the great reduction in wiring and cabling expenses also entails a substantial drop in system costs. Indeed, industrial bus systems can account for up to 30 percent of the investment costs of a production facility. A PLC transmission can sustain itself over a distance of 300 to 500 m. Beyond those distances, repeaters can be used to strengthen the signal.
Siemens (http://w4.siemens.de/FuI/en/archiv/zeitschrift/heft2_99/artikel06/index.html) and several electrical energy suppliers were fostering this new technology. Despite promising advantages for low cost automation no progress or a breakthrough so far have been reported.

In connection with network technologies **wireless connections** between sensors, controllers and actuators are coming into the focus of cost effective automation. The cost of wireless links will fall while the cost of wire-line connections will remain about constant, making wireless a logical choice for communication links. However, wireless links will not be applicable in all situations, notably those cases where high reliability and low latencies are required.

The implication for factory automation systems is that processing and storage will become cheap: every sensor, actuator, and network node can be economically provided with unlimited processing power. If processing and storage systems become inexpensive relative to wiring costs, then the trend will be to locate processing power near where it's needed in order to reduce wiring costs. The trend will be to apply more processing and storage systems when and where they will reduce the cost of interconnections. The cost of radio and networking technology has fallen to the point where a wireless connection is already less expensive than many wired connections. New technology promises to further reduce the cost of wireless connections, in particular Bluetooth.

Bluetooth™ goes back to a proposal that Ericsson had already developed in 1994 as a replacement for the mechanically vulnerable and inconvenient cable connections between communications products. In order to be as independent as possible of environmental and operating conditions, radio techniques were chosen in preference to the infrared transmission that was, at that time, already very popular. This made connections possible through cloth, leather and even walls, without line-of-sight contact. Having established a basic technical concept, Ericsson approached other manufacturers of portable electronic equipment with a view to establishing a world-wide standard. In 1998, together with Nokia, IBM, Toshiba and Intel, the Bluetooth™ Special Interest Group (SIG) was founded, which first went public in May 1998 and has meanwhile attracted more than 2100 member companies through a Bluetooth™ users' agreement. Every Bluetooth™ capable device can communicate with a range of other devices in a small wireless network – a so-called piconet. All the devices maintain a logical connection with one another that is only converted into a physical connection in the case of an actual data transfer.

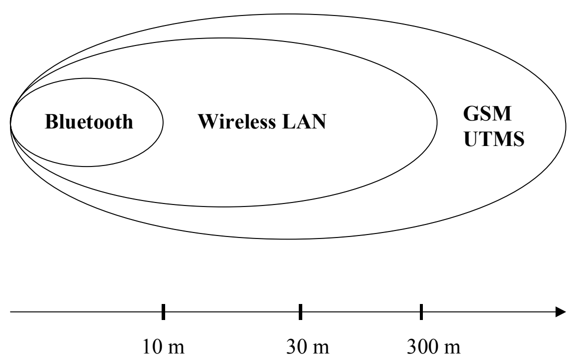


Fig. 16. Range of wireless connections (Siemens AG)

The maximum range of a Bluetooth™ connection is about 10 meters, there is, however, already a so-called 20 dB specification in preparation that will provide a range of up to 100 meters (Fig. 16), with, of course, a correspondingly high power consumption. More detailed information are available at: http://www.rfi.de/downloads/Bluetooth_UK.pdf

4. CONCLUSIONS

Low Cost Automation is a cross-sectional field of automatic control. Cost are the critical issue in the design and development of new components, instruments and the layout of manufacturing systems. Cost is also critical for the applications of robotics and autonomous systems in many manufacturing sectors. The decreasing cost of smart components and computer hardware and software technologies are producing significant changes in automation and particularly in manufacturing automation.

In addition to the technologies involved in the paragraphs above, manufacturing requires ever more information-intensive technologies to meet agile automation within the networked manufacturing enterprise. Thus, for example, new manufacturing automation architectures and systems engineering frameworks are important issues to consider.

Computer Integrated Manufacturing has meanwhile matured in today manufacturing processes, even in small and medium enterprises, and flexible manufacturing systems still requires significant information processing capabilities. The development of information processing and storage capabilities allowed new manufacturing automation architectures based on paradigms coming from the Artificial Intelligence and the Intelligent Manufacturing Systems.

Communication technologies play an ever more prominent role and the manufacturing plant becomes a place where interoperable and autonomous units embedding a digital intelligence transforming information flow into product flow in order to integrate all the aspects of the manufacturing processes over the whole product life cycle and the manufacturing systems life cycle across the entire enterprise (quality, maintenance, technical management, process planning).

Therefore life cycle assessment of automation systems with respect to total costs, integrated information processing in sensors, actuators and controllers, wireless networking and a software agent support for shop floor control and maintenance are the main challenges respecting a cost effective automation.

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