Developments and Trends in Monitoring and Control of Machining Processes

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This paper describes conventional and enhanced methods for the monitoring and control of machining processes with a limitation to cutting and grinding machine tools. The differences between the various methods and the corresponding equipment, software and strategies are considered as well as the reasons for the limited success of some of the existing systems in use. Furthermore, the requirements of future monitoring and control systems are worked out. Therefore a systematic analysis of present and future sytems and their components is made. Finally, the function of machining process planning and its influence on the performance and the reliability of the process is discussed.

1 Introduction

There are number of different conditions which lead to the installation of a monitoring system in an industrial manufacturing process. Modern manufacturing equipment has to be more and more flexible and has to run automatically. The machine tools have to work free of errors in order to insure economic usage. Figure 1 shows the vital importance of monitoring machining processes.

In this example the effective machining time of a machine tool has been increased from 10 to 65 per cent by monitoring and control systems /1/. In spite of the great possibilities to increase the effective operating time of machine tools by using monitoring systems as shown in figure 1 there is only a limited use of such systems in practice. Therefore in this paper not the well know commercial systems which are developed for the turning process /2,3,4/, the drilling process /5,6/ and the grinding process /7/ shall be discussed but mainly new and enhanced principles which are still under investigation. In order to classify the considered examples a systematic classification is made of the components of the systems.
During the last few years several new cutting materials have been introduced. For example, ceramics and CBN inserts for turning, milling and drilling and CBN grinding wheels have come in use. In order to provide a satisfying technical and economical application, these cutting materials have to perform under tougher working conditions than are usually applied.
In addition: during the last decades, materials have been developed which are difficult to machine. Some examples of these special materials are tough alloys, ceramics and reinforced plastics. For these reasons the predictability of cutting processes has decreased. Hence, industry needs systems, which detect tool fracture in turning, milling and drilling processes and the end of tool life in grinding. However in the future, many other process phenomena will have to be detected in order to improve the control of cutting processes. Apart from the detection of events to prevent failures, the registration of trends in running of machining processes is even more important, as it provides the basis for a interrupt-free and quality oriented process control free from troubles.

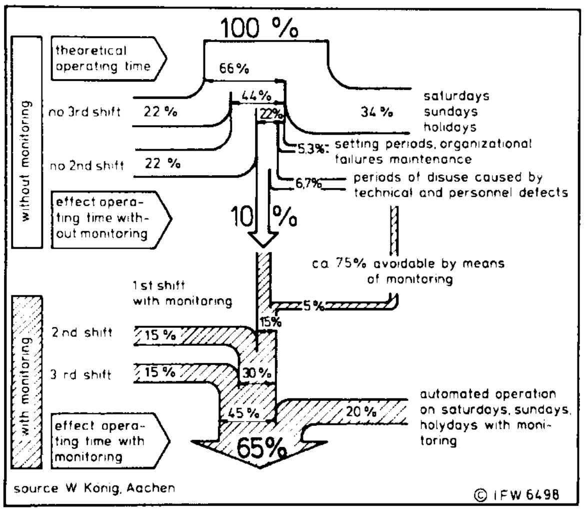

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Fig. 1: Economic importance of monitoring in manufacturing processes /1/

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- Prof. G. Chryssolouris
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Improvement of process control is required to save costs by reducing the non-productive time of expensive CNC machine tools. Figure 2 shows the vital importance of operating NC and CNC machine tools under optimum cutting conditions.

The investments associated with the use of expensive CNC-machine tools cause the man-cost curve and the tool-cost curve, as functions of production speed, to be steeper than with the use of conventional machine tools. For CNC machining it is important to select the cutting parameters much more carefully, otherwise costs will rise enormously and possibly exceed the costs of the conventional method. Due to these ecomomical aspects, it is often not possible to choose the lower and safer cutting conditions rather than the higher and more unreliable ones. Therefore, monitoring and control systems are necessary to obtain satisfying results even under critical conditions.

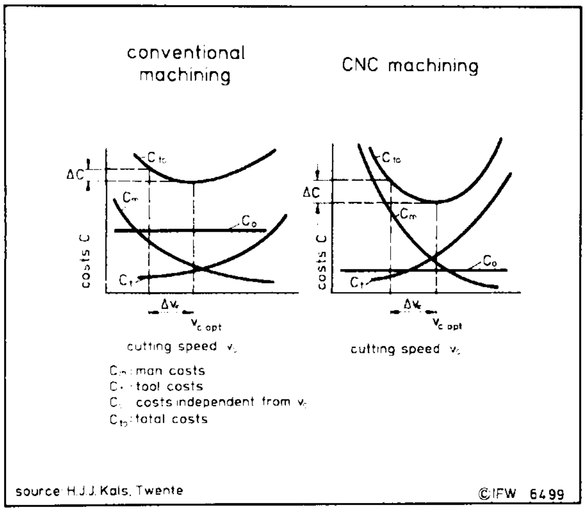

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Fig. 2: Machining costs per product as a function of the cutting speed, a: conventional machining b: CNC machining /8/

These systems can be used to support an operator working with modern machine tools running at high speed and using a lot of coolant, which makes human monitoring and adequate control almost impossible. In order to increase the productivity of rather expensive machine tools, monitoring and control systems can provide conditions for minimally attended or even unmanned production in a third shift or during the weekend.
These systems are both useful in a small batch or "chaotic" manufacturing, as well as in high volume production. Small batch production with few repeat orders needs a high level of organisation and preparation. It has become increasingly important to be

able to machine even the first part of a batch according to given specifications. For complex parts, e.g. those manufactured in the aircraft industry, the value added over different working stations increases enormously, hence the financial risk of a machining failure increases from working station to working station. In order to prevent rejects, control systems are needed which improve the quality of performance of machining and avoid machining failures.
Finally, monitoring and control systems are required for the recovery of interrupted processes. For this reason it is important to collect and store data recording the "history" of processes and products in order to be able to diagnose the reason for a process breakdown and to restart the process with a minimum loss of productive effort.

Before trying to optimize a machining process with monitoring or control equipment, it is necessary to consider the quality of process planning, since process and operations planning represents a vital function in the control of machining processes /8/. Both, the level and quality with which manufacturing processes can be controlled and the need for monitoring functions, depend strongly on the quality of the process and the operation plans. It is evident that if reliable process models were available for the calculation of adequate machining data and accurate time data, the need for monitoring would be less than presently is the case. Error-free NC-programs and reliable machining data which can guarantee controllable chip-flow and predictable product accuracy and tool wear also prevent the need for time-critical interference and subsequent recovery of machining processes. Accurate instructions for attaching, measuring, pre-setting tools etc. all greatly enhance the quality of control and thus minimize the need for monitoring. The same applies with respect to the utilization of equipment and an efficient control of material flow. They must be supported both by a continuous progress of the processes and scheduling based on accurate time data. Monitoring is therefore applied in order to

achieve safety
prevent fatal damage
prevent rejects
prevent idling of equipment
achieve an optimal use of resources.

2 Present Situation and Definitions

This paper relates monitoring to the following subjects: machine, tool, process, tool conditioning and workpiece as shown in table 1.

	time critical	non time critical
machine	• CNC-control • collision	• accuracy • thermal deformation
tool	• tool fracture • tool approach	• tool wear • tool presence
process	• chatter • force/torque/power • chip building	• coolant
tool conditioning	• dressing	• tool compensation
workpiece	• dimension in process • shape in process • roughness in process	• raw stock dimension • workpiece material • surface integrity

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Tab. 1: Presently monitored conditions in machining processes (time critical and non time critical)

The table also shows events, functions and conditions as objects for monitoring and control devided into two groups: time critical and non time critical. The time critical operations require a system response time within a range of milliseconds while the non time critical operations may take seconds or even minutes. The table, although incomplete, also covers some present areas in production engineering research. Fig. 3 shows all the components, which are required for monitoring and control systems.

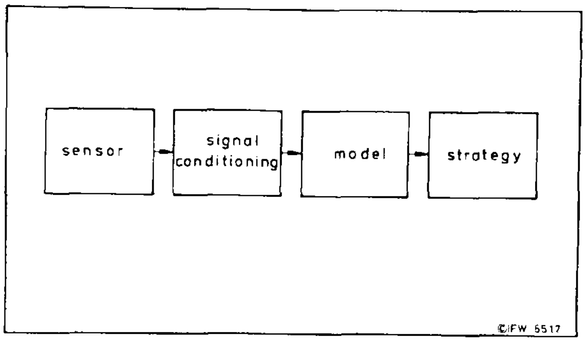


Fig. 3: Components of monitoring systems

1. SENSORS

A critical review of sensors for unmanned machining is given by Tlusty and Andrews. The problem that must be overcome in order to achieve the full potential of unmanned machining centers is the development of reliable and effective sensors for monitoring machine operation, ensuring efficient metal removal rates an taking correcture action in the event of accidents or breakages /9/.
In the use of sensors one can distinguish:

1.1 The physical principle of sensors like elongation and electric resistance etc. Nowadays piezo electric ceramics are becoming more widely used.

1.2 The technical application of sensors - direct or indirect - continuous or intermittent - post process or in process.

Apart from the well known difference between in-process and post-process control of machining processes, one can also distinguish between:

- input control and
- output control.

Systems which supervise the conditions of e.g. blanks, cutting tools, machine tools and clamping devices are called input control systems. In most cases, these systems simply reject input conditions which do not fulfil the requirements. Output control systems supervise the condition of the workpiece after machining.

1.3 Multi Sensor Systems dealing with several sensors, but supervising only one condition.

1.4 Intelligent Sensors which also perform local signal processing and conditioning.

2. SIGNAL CONDITIONING

Signal conditioning and signal processing deal with:

2.1 Data condensation in order to extract the relevant data. Hence the signals are amplified, filtered or A/D converted and selected.

2.2 The evaluation in the time domain, frequency domain, or with the aid of a cepstrum analysis.

3. MODELS

Models are required to relate the measured values to the monitoring and control subjects, e.g. the feed force signal is related to the state of wear of the cutting tool in order to prevent a failure of the tool. Models can either be physically or empirically based. A model has to be developed with the aid of mathematical equations and requires input data. Fixed models consist of constant parameters which have to be programmed before the operation starts. Adapting models makes it possible to adapt parameters as more information becomes available. Self learning models are able to adapt the parameters on the basis of their own observations according to a programmed strategy. Multi model systems contain more than one model for which the general performance depends on the interaction between these models.

4. STRATEGIES

4.1 Monitoring systems measure the conditions of the machine tool or of the process itself and indicate them on a display or activate an alarm waiting for an intervention of an operator. Monitoring systems are open loop systems.

4.2 Diagnostic systems monitor and try to find a functional or causal relation between failures in machining and their origins. Diagnostic systems are also open loop systems.

4.3 Adaptive Control Systems are closed loop systems. AC systems can automatically adapt machining conditions according to a given programmed strategy. The most simple systems activate a machine stop or a feed stop in the case of failure. More sophisticated control systems are ACC or ACO systems. ACC systems ensure that the material removal rate is kept at a maximum provided that given limits of forces, torque, power or temperature are not exceeded. ACO systems can optimize machining conditions with respect to a programmed target function e.g. minimum machining costs.

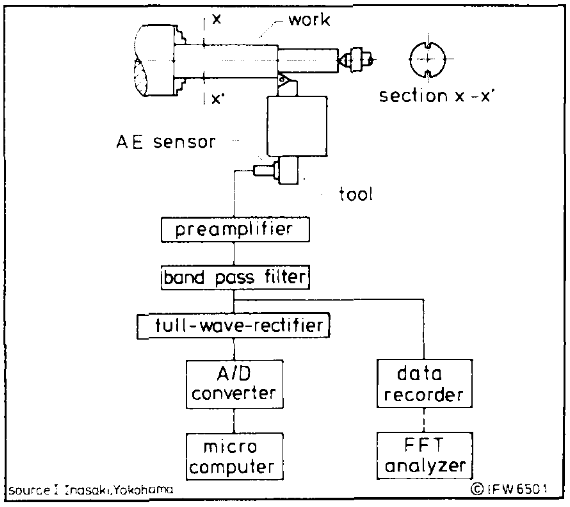
2.1 Examples of present sytems

Before considering examples of systems for monitoring and control, which have been developed up to the present day, criteria for the estimation of the various sytems are required. These criteria are as follows:

1. What kind of process is being supervised? (e.g.: turning, milling, drilling, ...)
2. What kind of supervision is being used? (e.g.: monitoring, diagnose, control, ...)
3. Which process conditions are being supervised? What is the aim of this supervision?
4. How many sensors are being used?
5. Which physical sensor principles are being applied?
6. What kind of signal processing and modelling is being used?
7. In the case of controlling actions: What are the actuating variables?

Many types of monitoring and control systems deal with the detection of tool wear /10,11,12/, tool chipping and breackage /13,14,15,16/ and nowadays there are efforts to detect the chip formation process for the use of defined cutting edges.

Figure 4 shows an experimental set-up for the detection of chipping for a single point cutting tool /17/. This is one example for the multiple use of acoustic emission sensors (AE sensors) in the monitoring of cutting processes with defined cutting edges.
Here the acoustic emission sensor is fixed to the tool shank. The detected signal is amplified, filtered, full wave rectified and fed to a computer for further processing. The sampling interval is 0,2 s. The amplitude level of the AE-signal AE(M) is defined as a mode of the probability density function of the signal shown in figure 5.



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kind of process	kind of supervision	aim of the supervision	number of sensors	sensor principle	number of models	actuating variable
turning	monitoring	detection of tool chipping	1	acoustic emission	2	-

Fig. 4: Experimental set-up for the detection of chipping of a single point cutting tool /17/

Frequency characteristics are analysed with an FFT analyser when they are needed. Figure 6 shows a typical example of the calculated AE(M) ratios normalized with the AE(M) value obtained at the beginning of the cut. The AE(M) ratio increases stepwise just after chipping. When the cutting tool chips on a large scale AE(M) is reduced due to the decrease in the actual depth of cut.

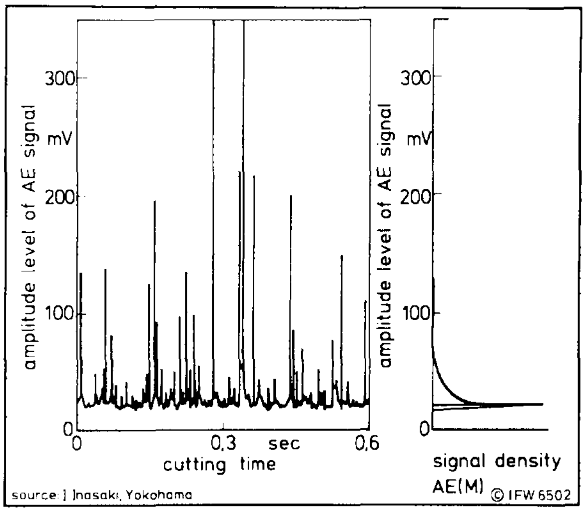

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Fig. 5: Definition of the AE(m) signal /17/

It has been confirmed after many cutting tests that the AE(M) ratio increases or decreases stepwise, depending on the scale of chipping when the cutting tool chips. The frequency characteristics of the original AE signal are analysed with an FFT analyser. As shown in figure 7, the power of the frequency component between 0 - 300 kHz increases markedly when the cutting tool chips.

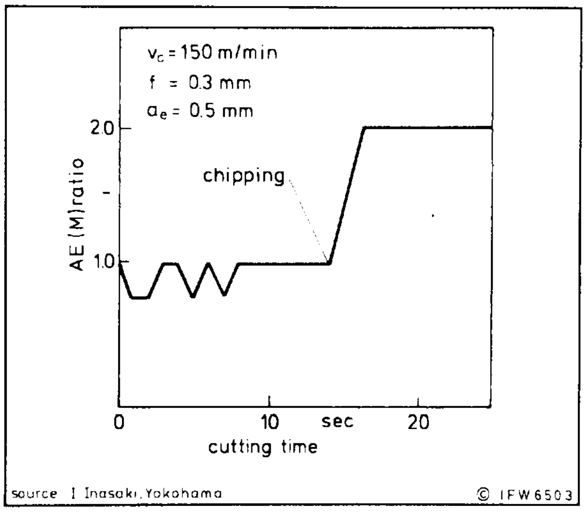

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Fig. 6: Change in the AE(m) signal when chipping occurs /17/

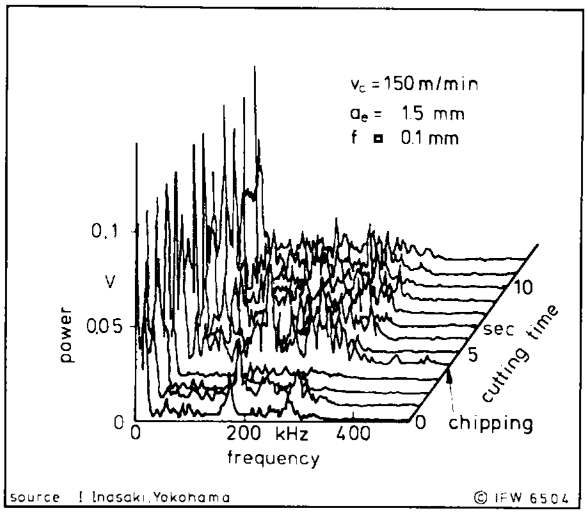

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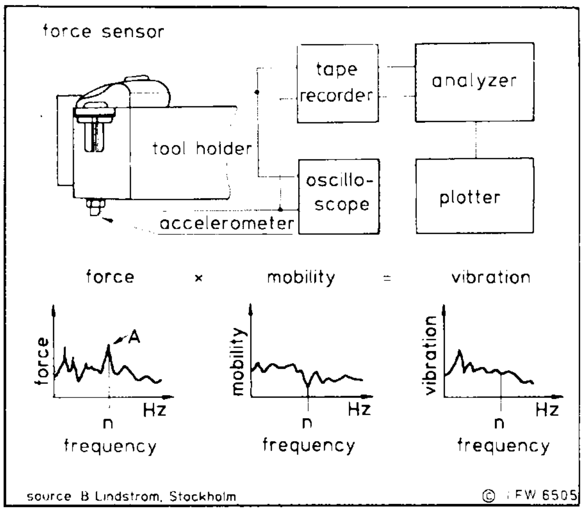
Fig. 7: The frequency characterized of the AE(M) signal in case of chipping /17/

The second example for supervising a turning process deals with the measurement of the segmentation frequency in the chip formation process /18,19/. By comparing the information from a conventional accelerometer and a force sensor on the one hand with metallographic samples of the chips on the other hand, extended experiments and tests have shown that the segmentation process in the cutting zone can be measured. By using FFT analysis of the signals of the transducers the transfer function of the system can be determined. The new force sensor which has been developed for measuring dynamic forces from the insert, is applied between the insert and the shim.

Figure 8 shows the relationship in graphic form between force, mobility and vibration with respect to frequency. Note in figure 8 that the high force component A at frequency n is eliminated by a low mobility at n, so that no peak is obtained in the vibration spectrum. It is therefore unacceptable to look for amplitude peaks in the vibration spectrum only. With the new force sensor and conventional accelerometers a very accurate analysis can be performed and every frequency peak in the spectrum can be determined. The measuring equipment as shown in figure 8 used for the described system is a digital spectrum analyser connected to a plotter.



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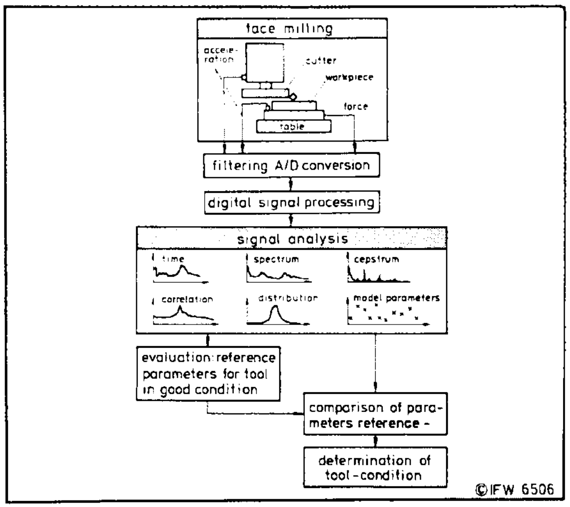
kind of process	kind of supervision	aim of the supervision	number of sensors	sensor principle	number of models	actuating variable
turning	monitoring	detection of the chip segmentation frequency	2	-force -acceleration	2	-

Fig. 8: Set-up for the measurement of the chip formation frequency /18/

By recording the signal from the transducer with a tape recorder, the frequency range can be expanded. The accelerometer is a centre-mounted compression type. This design gives moderately high sensitivity and can withstand high levels of continuous vibration and shock. The force sensor used is a specially designed force transducer. Like the accelerometer this force sensor also uses a piezo electric element which, when dynamically compressed, produces an electrical output, proportional to the dynamic force transmitted through it. In order to measure the dynamic cutting forces as closly as possible to the cutting zone the piezo electric element is inserted between the carbide insert and the tool holder. This investigation has shown that the relationship between the chip formation process and the dynamic cutting forces in the shear zone is probably one of the essential features of the cutting process.

For the next example figure 9 shows an experimental set-up for broken-tool detection in face milling by Cepstrum Analysis /20,21/. In the case of a complex workpiece geometry cut by a milling tool with ceramic inserts there is only a small chance of detecting the breakage of an insert, because the force pulse, known from breaking carbide inserts, is missing. Therefore one force sensor and two accelerometers are used to have a look for characteristics in the cutting force which corresponds to a missing insert. The signals are filtered and then A/D converted. It has been shown that the cepstrum analysis /22,23/ is an adequate algorithm for this purpose. The cepstrum analysis is a method for the deconvolution of signals. Applied to the measured cutting force the result shows some characteristics of the time series of the running inserts.

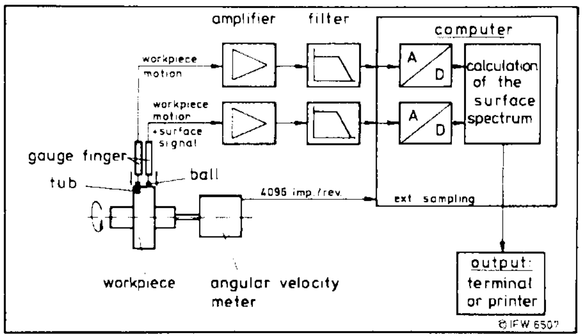


kind of process	kind of supervision	aim of the supervision	number of sensors	sensor principle	number of models	actuating variable
face milling	monitoring	detection of broken tool	3	acceleration	3 - time - frequency - cepstrum	-

Fig. 9: Experimental set-up for the detection of tool breakage in face milling

There are many requirements for supervision of the grinding process and the grinding wheel conditioning process. One example for the optimization of the grinding cycle is given by S. Malkin in /39/. Here an optimization method is described for minimizing plunge grinding cycle time while satisfying required surface quality requirements. The optimization method consists of two optimization strategies: (1) identifying the maximum allowable radial infeed velocity, and (2) modifying the shape of grinding cycle for optimal accelerated spark-out. The first strategy has been already applied to both on-line and off-line optimization of conventional grinding cycles. Accelerated spark-out is achieved by overshooting the infeed control followed by backing off to the final part dimension. Coupling these two optimization strategies together provides a practical optimization method for computerized adaptive control optimization (ACO) grinding systems.

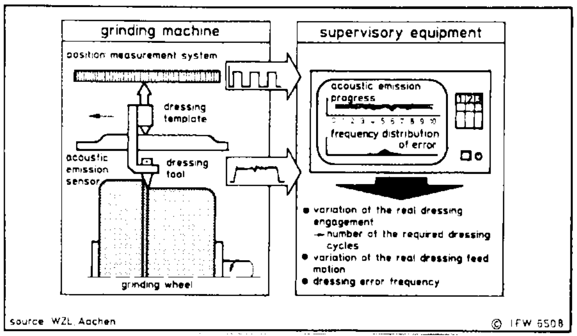
The first example for supervising the grinding process deals with a geometric control loop, used to avoid machining failures in waviness on the workpiece surface caused by chattering in the machine structure /24/. Figure 10 shows the experimental set-up for the detection of geometric machining failures which are neither failures in diameter (1st order failure) nor failures in roughness (3rd order failure) but failures in waviness (2nd order failure).



kind of process	kind of supervision	aim of the supervision	number of sensors	sensor principle	number of models	actuating variable
grinding	AC	avoiding of surface waviness	2	gauge fingers	1	active dampers

Fig. 10: Experimental set-up for detection of geometric machining failures /24/

In order to cut off the geometric failure on the workpiece surface from oscillation or chattering of the grinding wheel which both have the same frequency and amplitude, a special sensor is used. The sensor consists of two parallel gauge fingers. One gauge finger touches with a ball in order to detect both workpiece oscillation and the waviness signal from the surface. The other gauge finger has a tub which detects the workpiece oscillation only. After amplifying, filtering and A/D conversion the two signals can be subtracted so that only the interesting waviness signal remains. Active dampers or acoustic emission absorbers may be actuated in order to decrease the cause of chattering which induces waviness.



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kind of process	kind of supervision	aim of the supervision	number of sensors	sensor principle	number of models	actuating variable
dressing of grinding wheels	monitoring	optimization of the dressing process	1	force or acoustic emission	1	-

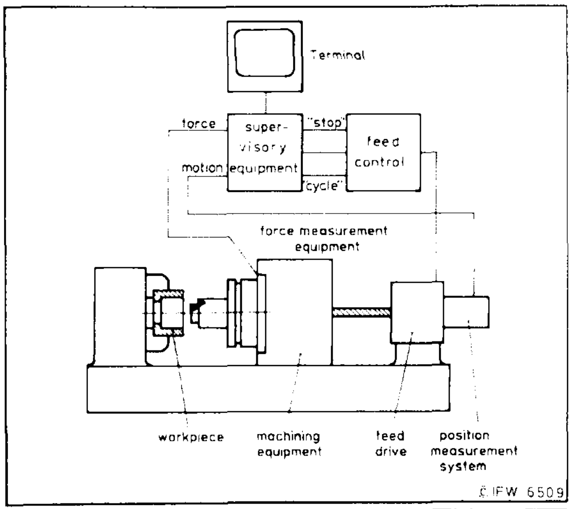
Fig. 11: Experimental set-up for the supervision of the dressing process /1/

Besides the life of grinding wheels the supervision of the dressing process has become increasingly important /25/. Fig. 11 shows an experimental set-up based on the detection of acoustic emission /1,26/. This system can detect the actual dressing engagement and feed speed.
The dressing engagement is measured indirectly by force or acoustic emission sensors while feed motion is directly measured. A teach-in modus with optimum dressing conditions is necessary for the system to be able to learn the desired values of the indirect measurement variable of the dressing engagement as a function of feed motion. In case of any deviation between actual dressing cycle and the learned optimum cycl the system would provoke a repetition of the dressing process. By the use of this supervising system the stability of the process can be increased and unnecessary dressing cycles are avoided.

At last figure 12 shows the set-up of a simple control system for tool condition supervision in a drilling process with more than one cutting edge /28/. Due to the described system, a high volume production process has been supervised with great success since 1984 in an industrial company.
The system measures feed force and feed motion. The feed force sensor can detect fracture and wear of the cutting edges in process, in a continuous and indirect manner. The feed motion sensor is necessary to distinguish the zones of different diameters in the workpiece. The definition of limited force values in order to detect tool wear or tool fracture is not applicable when using edge or step drills. This is the reason why the feed force is oscillating with a large amplitude without any tool failure. In the case of complex machining as mentioned above the method of "pattern recognition" seems to be helpful in the supervision of the process. Figure 13 shows the machining of a screw cap as an example for "pattern recognition".
The raw stock is forged and the tool has two cutting edges. For this special case the feed force as a function of the feed motion shows three ranges of machining:

1: machining the large diameter
2: machining the small diameter
3: machining the plane area

For supervising this drilling process a system was developed, which is based on a micro-computer. The feed force is detected by a simple, customary in the trade, piezo ceramic force sensor, which is not very expensive but reliable. The feed motion is detected



kind of process	kind of supervision	aim of the supervision	number of sensors	sensor principle	number of models	actuating variable
step drilling	AC	detection of tool breakage and tool wear	1	force	pattern recognition	feed motion

Fig. 12: Simple set-up for the supervision of a drilling process /28/

by a rotation sensor on the spindle motor axis. The terminal is useful for monitoring the process parameters or for giving advices to the operator. Before starting the production a teach-in cycle has to be performed in order to get the typical force values as a function of the feed motion by machining a raw stock with ambient geometric tolerances. Then an upper force value is calculated by the system itself for the different zones of machining. When machining the following workpiece, the actual force value is equivalent to the tool wear. The upper force limit, determined by the system provides preventive action against a sudden tool fracture or unacceptable tool wear which appears gradually. When this occurs, the system activates an alarm and stops the feed motion. This set-up is an example for a simple AC system with a binary actuating variable. The actuating variable is the feed motion which can be either "ON" or "OFF".

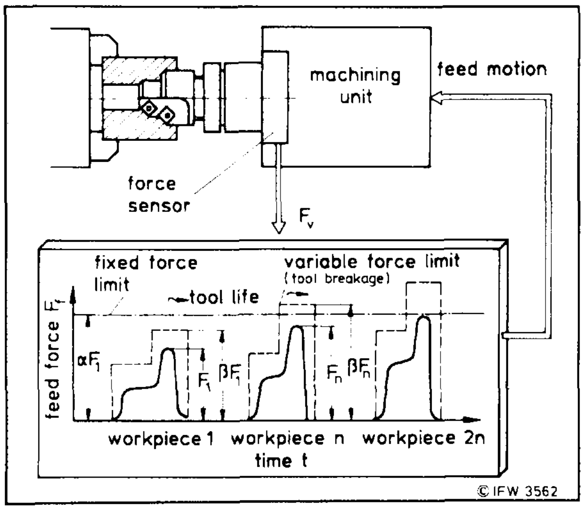


Fig. 13: Example of supervision of a drilling process /28/

2.2 Assessment of present systems and future requirements

There is limited use of monitoring and control systems in industrial practice. Human skill is still necessary in order to run complex machining processes. Existing systems for monitoring and control are built only for special tasks. For example, there are systems which supervise only one kind of process with one workpiece material to be machined with only one set of machining parameters. Another reason for the failure of the most monitoring and control systems is the application of unsophisticated models. So in many cases there is a little correlation between the measuring variable detected from the sensors and the interesting process variable /27/.
In those cases where shifts are unattended, the work carried out is usually restricted to simple workpieces. Characteristics of such workpieces are:

1. Only cast iron, no steel, is machined in view of the risks of jamming chips.

2. Only simple products with low geometric tolerances are machined.

3. Only repetitive work is carried out, e.g. drilling of a great number of identical holes which can be monitored easily

In order to improve the supervision of machining processes some further requirements are mentioned below:

1. To increase reliability it is necessary to use both, monitoring and control systems, instead of monitoring systems only.

2. The second possible improvement of process control is to increase the quality of the control. Present control systems merely stop spindle rotation and/or feed motion. Today, the demand for systems with continuously controlled variables has increased.

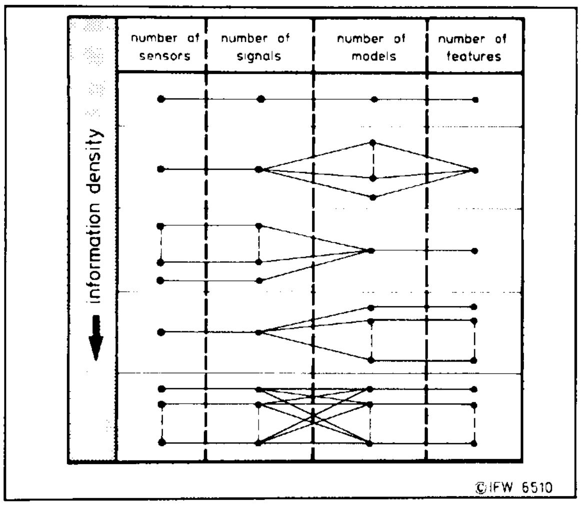
3. There is a high demand for improving measurements by using more sophisticated sensors and more data by the use of accomplished models in order to get a better correlation between sensor signals and process conditions.
4. The control systems which are the subject of present investigations or which have to be developed in the future are more flexible than the systems of today.

3 Future Trends

3.1 New Principles

In order to fulfil the requirements considered in chapter 2.2, new enhanced principles for monitoring and control are necessary. For example: The use of more than one sensor for monitoring machine tools or machining processes gives an extended survey of the interesting features, as most process variables have an influence on one another. Those sytems are called "Multi-Sensor-Sytems". They need highly sophisticated models or even more then one model to work up the sensor signals. Furthermore, the sensors have to be applied as closely as possible to the feature of interest to be able to obtain signal which closely corresponds to the controlled variable.
There are several possible combinations of sensors and models. In the most practical applications one sensor measures one physical quantity only. The measured variable is built up by one model which delivers one monitored feature of the measuring object. Yet, there are better ways to obtain an optimal signal:
The first is to build up the signal of one sensor through several models in order to get more interesting features of the object by one sensor. These sytems are called "Multi-Model-Systems".
The second possibility is to evaluate the signals of several sensors through one model in order to get one interesting feature. These systems can produce more accurate results because the model receives more detailed information about the process.
Table 2 gives a survey of the principles mentioned above.

The different possibilities are the number of sensors, signals, models and the reported conditions. The increase of information density is also indicated. The use of more sensors and models results in a more reliable and more flexible supervising process and increases the feasibility of a better control. At present, there are few systems under investigation which work as described above. An example of present



Tab. 2: Some possibilities to combine sensors and models

systems is shown in figure 15 /29/. Before considering this example, some definitions about cutting data are made in figure 14 /29/.

All cutting data which give acceptable results when only the specific technical limitations are taken into account are called Technical Cutting Data (TCD, see figure 14). Most cutting data used in industry are obtained from recommendations found in standard or company files (Recommended Cutting Datas (RCD)). Such cutting data are usually rather conservative or "safe" and consequently uneconomic. Cutting data which take into account both economic and technical limitations and which are taylored to specific conditions, are called Optimum Cutting Data (OCD). The values of the machining parameters are usually higher and more critical in a technical sense than RCD. Cutting data which take only the economic situation into account and which disregard the technical limitations, are called Global Optimum Cutting Data (GOCD).The values are usually "unsafe" as regards the technical objectives. Systems used in the operation planning department produce cutting data belonging to one of these levels. Most systems deal only with RCD. A few systems give limited OCD, i.e. only the cutting speed is optimized. One aim of a ACO System could be to create and manage the basic cutting data in such a way, so that during the machining operations OCD can be successfully applied, regardless of changes in the process during operation. With a working ACO System, OCD will be reached during cutting /29/. This of course implies the necessity of updating and tayloring the basic cutting data in order to provide more accurate starting data.

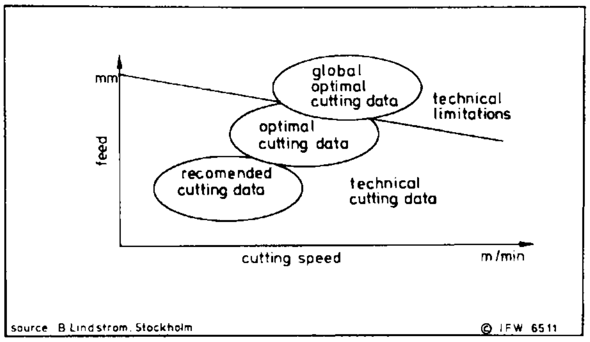


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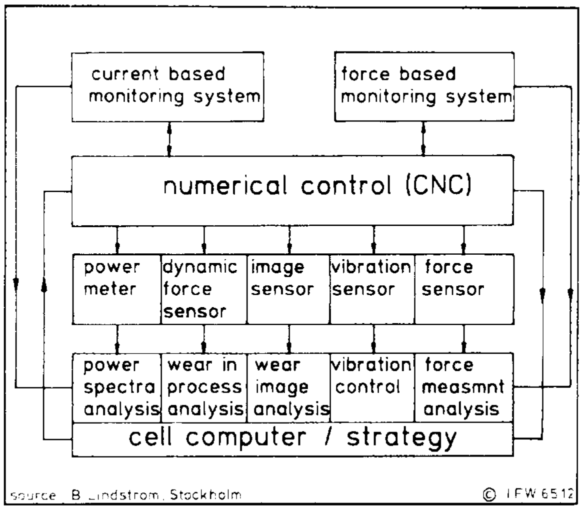
Fig. 14: Definitions of data types in cutting /29/

The AC sytem /30/ which has been developed is based on the following control and monitoring functions, devided into different levels as seen in figure 15:



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kind of process	kind of supervision	aim of the supervision	number of sensors	sensor principle	number of models	actuating variable
turning	AC	- tool wear / breakage - chipping - collision - vibration - motor current	5	- power - force - image - vibration	5	machining parameters

Fig. 15: Example of a "Multi-Sensor-System" and a "Multi-Model-System" /29/

* advanced process monitoring for catastrophic failure
  - motor current monitoring
  - tool flank wear
  - tool breakage
  - vibration
  - collision
  - chipping

• adaptive control constraint, ACC with limited feed-back
  - control with respect to forces
  - control with respect to vibrations

* adaptive control optimization
  - optimization with respect to maximum production rate and/or minimum cost

In order to perform these functions the system requires different kinds of measured data. To monitor the cutting process, two independent commercial systems are being used. At the same time, five independent measurement systems have been developed:

* a power spectra analysis system
* a high frequency tool signal analysis system
* a directly working, optical flank wear measurement system (between cuts)
* a vibration measurement system
* a force measurement system

The systems present intelligent modules in the distributed AC system are controlled by a cell computer employing real time techniques. With the force sensor and the vibration sensor, an ACC system is built in order to be sure not to exceed the technical limitations. The dynamic force sensor and the image sensor are needed to analyse tool wear. With the dynamic force sensor, an in-process detection of progressing tool wear is possible. Furthermore, a tool cracking could be detected. The image sensor can be used post process only. It delivers an absolute, directly measured and reliable value of the flank wear of the tool, which can be used to update the data bank. In this example, a "multi sensor system" and a "multi model system" is realized at the same time.

The second example of new monitoring and control principles deals with the optimization of internal grinding by micro-computer, based on force control /31/. Here a digital controller /32,33,34/ is used. The closed loop force control can give the following advantages:

- Safety of operation handling vitrified bonded BN wheels
- "First cut" detection during approach rates up to 10 mm/sec
- Decrease in grinding time
- Optimum reduction of non circular boring conditions
- Off line identification in order to tune the coefficients of a chosen control algorithm.

Figure 16 shows the normal grinding force for a) digital closed loop control in comparison with b) the analogue closed loop control and c) the behaviour in conventional grinding.

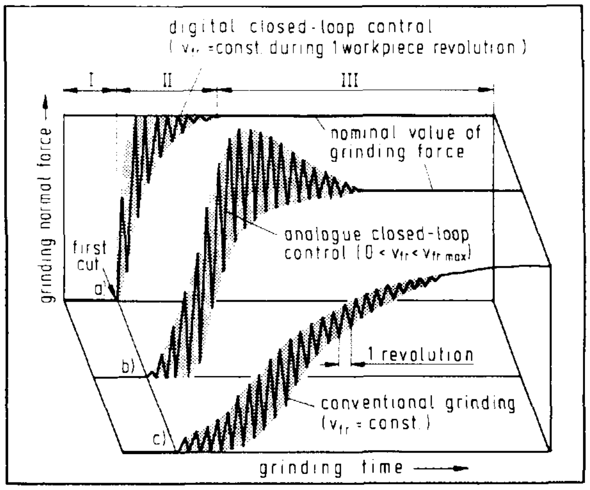
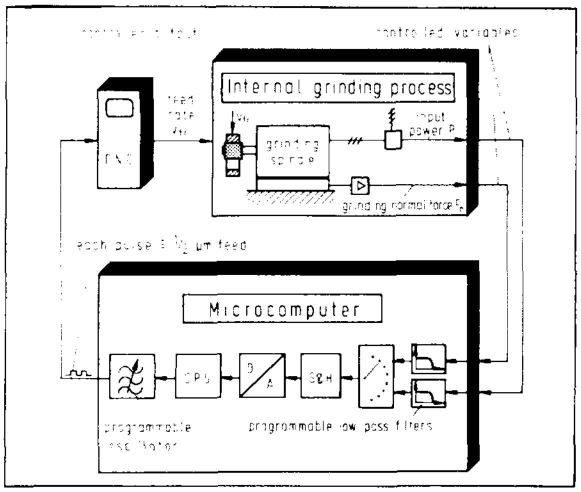


Fig. 16: Effects on grinding non circular borings using different types of process control /31/

Phase I must allow high and constant approach feed speeds in order to minimize time of air grinding. The only activity during approach is the detection of the first cut which has to go together with a short response time in order to realize fast approach rates. Upon the detection of the first touch, phase II has to be started during which a quick transformation to steady grinding conditions has to be carried out. Force controlled grinding without any limit in controller output results in the reproduction of non-circular contours. Conventional closed loop control systems therefore do not allow the output of negative feed rates in order to prevent a tool retraction. Thus grinding wheel overloads are provoked after the first cut in the case of machining non circular workpieces. When the workpiece has been ground into a circular state due to the digital control loop constant force grinding starts in phase III. In this phase an optimization of the quality control can be carried out. Figure 17 shows the hardware set-up for the digital control loop.

The normal grinding force is measured with a piezo-electric dynamometer located below the grinding spindle. Power measurement is obviously a less expensive solution than force measurement, but grinding tests show that depending on the size of the spindle, power measurements are associated with a considerable dead time, which may cause too long a response time. In this example a 16 bit microprocessor, programmed in PEARL, is used for process identification and digital control. The variable actuated through the CNC control, is the feed rate vfr. An essential part of the digital controller is the control algorithm. The control behaviour starting with the first touch, is the dominant criterion for its choice. The nominal value of the grinding force has to be reached within the shortest possible time without an overshoot. Every first cut input represents a step function which has to be transformed into an optimum control signal. In addition, the controller has to be able to deal with dead times, as they occur power measurement is used as a control variable. For this task a so called "dead-beat-controller" can be applied. From simulation of the grinding process and the use of different control algorithms this type of controller was found to be most effective. The application for internal grinding requires first the tuning of the controller coefficients. Therefore, the behaviour of the controlled system has to be determined. Figure 18 illustrates the concept and the linkage of process identification and digital closed loop control.



kind of process	kind of supervision	aim of the supervision	number of sensors	sensor principle	number of models	actuating variable
internal grinding	digital AC	optimization of the grinding process	2	-force -power	one adapting model	feed rate

Fig. 17: Control loop for internal grinding /31/

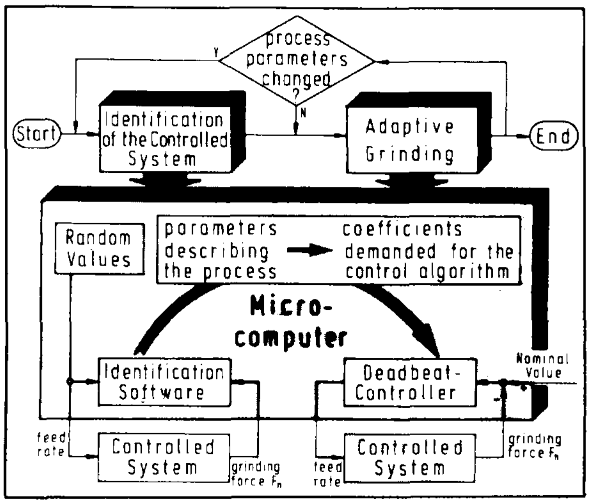


Fig. 18: Concept of process identification and control /31/

3.2 Enhanced strategies

3.2.1 Learning and decision making systems

The first example of enhanced control strategies deals with learning systems for process supervising. Figure 19 shows the functions which are required for a learning control system.

The objects which are usually supervised are the machine tool, the tool, the machining process and the workpiece. For the determination of the relevant conditions the system requires sensors, signal conditioning equipment and mathematical models as mentioned above. In conventional systems a deviation between actual values and required values is directly

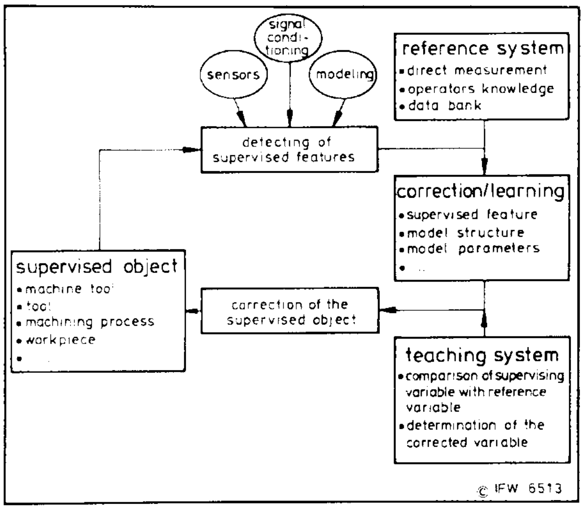


Fig. 19: Structure of a learning control system

reduced by adjustment of the control variable. However, the adjustment process in learning systems is more complex. In one subsystem an adjustment and learning process takes place. The adjusted variables include not only the control variable of the object as in conventional control systems but also the parameters of the control strategy, the control algorithms and the models which are applied. Therefore a reference system which delivers the required values for these parameters is a precondition. The source of the required values may be a direct working measurement system, which delivers values of high reliability or data which come directly from the operator at a terminal or from databanks, which contain old highly reliable data. The third system is a teaching system, which compares the measured process parameters with the values of the reference system. The teaching system gives advices to the adjustment of the adaptive and learning system, whose variable has to be changed. There are two possible ways to adapt a model to varying conditions. The first is to change the model parameters and the second is to change the model structure. The latter method, however, is very difficult, as a lot of "meta"-knowledge is required. The aim is to make a control algorithm as adaptable as possible to the actual process conditions. With increasing experience, reference systems will become more and more reliable and promote the use of adaptive and learning control systems.

3.2.2 Rule-based systems

The second example of enhanced strategies shows the system set-up for a rule based and decision making system for the control of machining processes /35/. The primary difference between an automated machining workstation and an intelligent workstation is that the intelligent system is capable of making decisions based on significant information about the state of the system. Intelligent control of machining processes can, in general, be treated as a decision making problem. Most of the decisions made by an intelligent controller must be made within a relatively short period of time. An adequate response to changing system conditions and events such as tool wear, machine breakdowns and other failures must be made within seconds or milliseconds in order to guarantee the safety and reliability of the process. The execution of a decision making process can be formulated in a manner similar to the one in which a human being would proceed. The decision execution can be thought of as consisting of four subsequent steps :
In step 1, select the alternatives at a given decision point.
In step 2, select the applicable criteria to evaluate the different alternatives.
In step 3, calculate or estimate the selection parameters for each ofthe proposed alternatives.
In step 4, through application of the decision rules: select the best alternative.
This decision making method can be concisely expressed in a decision matrix format where the matrix elements indicate the evaluation of each alternative with respect to the criteria. This method describes a framework in which AI (artificial intelligence) techniques /36,37,38/ can operate in conjunction with operations research concepts. This approach allows the use of qualitative as well as quantitative information in the decision making process. Yet decisions can be executed within the reaction times required by the control of a machining operation. In addition the approach is expressed in general terms and can be used to model and control any workstation.

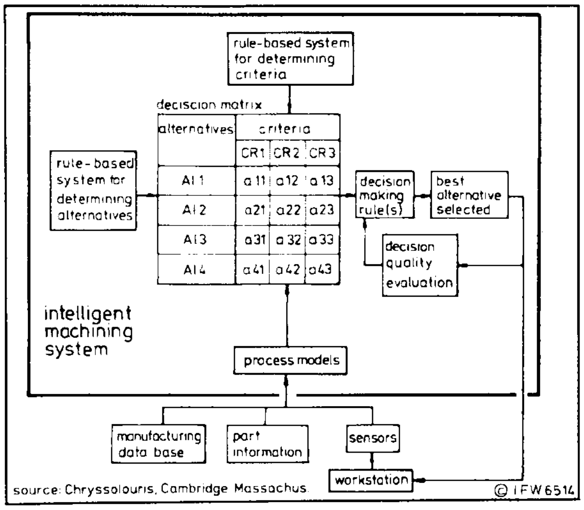


Fig. 20: Basic structure of an intelligent machining system /35/

Figure 20 illustrates the structure of an intelligent machining controller. The core of the system is a decision matrix , the columns representing the different criteria which must be considered, and the rows representing the different alternatives which can be considered. The matrix elements are the different values the criteria may have for each alternative to be considered. The system consists of a number of significant elements which can be described as follows:

- A rule-based system for the selection of the criteria provides the connection between the machining operation and the objectives which are set in the higher level of the manufacturing hierarchy. The module selects the criteria which have to be considered during a machining operation.
- A rule-based system for the selection of the alternatives produces the decision matrix containing a set of feasible alternatives from which the best alternative has to be selected. In general, the alternatives represent a set of process input parameters.
- The process models, based on sensor information as well as part information and information from a general manufacturing data bank, provide the decision matrix with values of the alternatives with respect to the different criteria.
- A set of decision making rules are applied to the decision matrix to select the best alternative. This element of the structure in conjunction with a sub module for evaluating the quality of the decision, selects the best alternative whenever a decision must be made.

Using this approach, decision will be made quickly and within the time frame required by an intelligent machining workstation. Figure 21 illustrates the structure of this module in greater detail.

In this example several sensors are applied to the decision making system for a connection to a cutting process:

- Force sensors which sense the cutting force along a three coordinate axis.
- Temperature sensors which sense the tool temperature as accuratly as possible.
- Vibration sensors which will sense some type of vibration (e.g. acoustic emission, etc.) related to the machining process.

These sensors will feed their signals into three independent process models which process the signals,

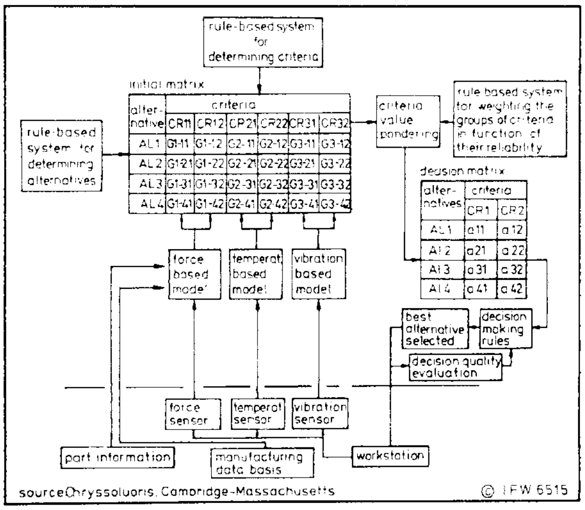


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Fig. 21: Example of an intelligent machining system /35/

providing the values for an initial decision matrix. In figure 21, the values are depicted as a_{ijk}, where i denotes the sensor from which the value was generated, j refers to the alternative to be considered, and k refers to the criteria. Figure 21 gives an example of two criteria, criterion 1 and criterion 2 which must be considered. The initial matrix contains values for the different criteria which are independently generated by the three independent process models. The final decision matrix is determined by a small rule-based system which established weighting factors based on information about the particular machining operation to be controlled as well as the reliability of the three sensors. After the preliminary evaluation of the initial decision matrix , a final decision matrix is constructed. The alternatives in the final decision matrix may be variations in the feed rate given as a percentage of the initially programmed feed rate. The criteria are the required cost and time of the remaining machining operation for each corresponding alternative. After the construction of such a decision matrix, the next step is to select the best feed rate by applying a set of decision making rules. The concept, as presented above, for controlling the machining process provides a number of significant advantages over conventional adaptive control techniques and/or expert system approaches:

- The time required to make decisions has been substancially reduced by constructing the system of small, reasonably-sized modules and, as will be discussed further in the next section, providing two levels of decisions:
  quick decisions for machine tool safety and protection, and more lengh decisions for choosing the optimum selection of alternatives.

- Provided that a number of independently established process models can be used, the result of any change in process parameters will be more accurately simulated by the new intelligent controller than by conventional techniques based on a single sensor process signal.

- Because of the modular structure and the generic manner of formulating the process models, the intelligent controller is very flexible. A wide variety of tool conditions, materials and geometries can easily be included within the general controller structure described.

- Finally, by utilizing a variety of sensors, a maximum amount of information is considered in making control decisions; the quality of the decisions is therefore likely to be better than decisions based on information from a single sensor.

3.2.3 Recover strategies

Recover strategies are absolutely necessary for automatic problem solving and automatic restart of machining processes. For this, a description of relevant events and conditions of the process in progress has to be stored in a kind of "logbook". The history of the process must be long enough to be able to reconstruct the cause of a failure. One of the aims of process recovery is to decrease the non productive time of a machine tool after a failure has occured. It is advantageous to obtain signals from more than one sensor. The sensor signals may be binary (On or Off) or describe a continuous range which must be A/D-converted. All signals are evaluated and the results are stored in a buffer. New values continuously replace the oldest values in the buffer. In the case of failure the ranges of values belonging to the respective measured quantities up to the moment of process breakdown have to be compared with known histories of possible failures in order to reason the origin of a failure by failure analysis. From that, one of the failure recovery scenario has to be selected and carried out before the machining process is to be continued.

3.3 The function of process planning

The monitoring and control of machining processes is both dependent on an accurate and reliable hardware equipment with suitable signal processing and modeling on the one hand and the work of the process planning department on the other. The significance of process planning as a part of the monitoring and control loop increases with batch size and lower repeat frequencies of the batches. The reliability of the future generative CAPP-systems strongly depends on the one hand on the models which are used to describe the behaviour of machining processes and on the other hand on the reliability of the acquired data. Experience shows that the development of general applicable process models is very difficult if not impossible, since one has to rely on empirical knowledge. As a result of this, the significance which process planning can have in relation to process monitoring is determined by the use of

1) Unit-dedicated data /8/
2) Model referenced monitoring /41,42/

Unit-dedicated data

In practice, the accumulative effect of the different systematic influences, which cannot be described by the over-simplified process models is experienced as unreliable behaviour. Apart from using statistics, the effective reliability of the models can be increased by a restriction of the application area and the assignment of dedicated data-sets for different environments. A more generic use of process models is possible when the model constants are adapted to different machine tools, material batches, environmental conditions etc. For instance, since we know that tool life depends on the dynamic behaviour of machine tools which, however, cannot be quantified, each machine tool should be assigned its own (unit) data set for the calculation of tool life.

Model referenced monitoring

During process planning, machining data are assigned to each program block of a NC-program which deals with a machining operation. This data can also be used as reference values for the monitoring equipment. When the machining data are calculated with the aid of mathematical models, the systematic deviation which arise between the calculated and the actual values can be used either to adapt the coefficients used in the models or to change the structure of the models. The measuring actions carried out by the monitoring equipment must be synchronized with the block by block execution of the NC-programs. Presently available monitoring systems have to be tought in a learn mode which requires test runs to be made on the machine tools. The method cannot efficiently be used in small batch manufacturing and certainly not in relation with precalculated cutting data. Offline programming of monitoring equipment would need additional work to be carried out during process planning. But no doubt, new communication standards for NC-controllers, like the LSV2 standard, will make it possible to program automatically future monitoring equipment automatic by the NC-controller during the execution of the NCprograms. The possibility of reconfiguration of monitoring equipment controlled by supervisory cell computers is already present in some experimental set-ups /40,41/. A complete evaluation of measured process data has to be performed on three hierarchical levels as shown in figure 22 /8/.

The time critical Adaptive Control Constraint (ACC) loop is necessary to invoke immediate action in order to avoid damage whenever given threshold-values are exceded. The selection of the threshold values is a matter of process planning which in future can be carried out automatically.
The Adaptive Control Optimization (ACO) performs a statistical evaluation of the (same) measured data in

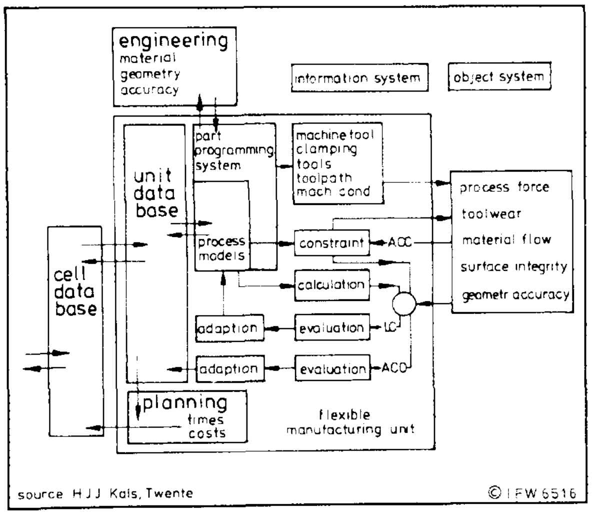

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Fig. 22: A three level control system /1/

order to adjust the coefficients of the process models for pre-specified conditions (units). This control loop shows a considerably larger time-constant when compared with the ACC. The improvements in process control must be established through the planning of the process. The prime objective is to extend the range of validity of the process models by adaptation of the values of the coefficients to the behaviour of different units. ACO-functions can be installed in bypass of the process planning department in order to perform a more time-critical function in a shorter loop. The method which optimizes by itself is not the most effective one since it is obviously used to compensate permanently the effect of inadequate process planning. The method is difficult to be applied in small batch production. At the third hierarchical level, the learning control (LC) loop monitors the ACO-loop. When the ACO-function cannot converge to a better solution by adaption of coefficients, the LC-function can subdivide the initial application range into smaller ranges or may "intelligently" be able to change the structure of a process model. The application of AI-techniques in future will be indispensable here.

4 Conclusions

Monitoring and control systems can increase the controllibility and reliability of machining processes. However, the present developments are still in their infancy. In this paper the actual state of the development of monitoring and control systems is described. Conventional equipment and strategies have been considered as well as new and more enhanced strategies, but much has yet to be done before the successful application of supervising systems becomes common. Examples of enhanced strategies are:

- Adaptive control optimization systems which have an active influence on the process in a wide range
- Multi-sensor-systems and multi-model-systems which can increase the quality and the quantity of the information about the processes to be supervised
- The use of rule based systems and learning systems which must work complementarily to algorithmic systems and provide the possibility of a flexible use of expert knowledge.

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