A REVIEW OF THE MONITORING AND CONTROL OF MACHINE TOOLS

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ABSTRACT

This paper describes conventional and enhanced principles for control and monitoring of machining processes. Special emphasis is placed on applications to cutting and grinding tools. The various components of a monitoring system are described, and trends in control and monitoring using special purpose sensors for Computer Numerical Control (CNC) machining operations are presented. Finally, the need to develop in-house strategies at the Faculty of Engineering, The University of the West Indies, for the adoption of CNC technology to the Caribbean region is discussed.

1.0 INTRODUCTION

The increasing flexibility and automatic operations of modern manufacturing equipment, together with developments in new materials and optimal tool life requirements, have resulted in the growing need for monitoring and control of machine tools.

When machining ferrous materials, the main properties influencing tool wear mechanisms and cutting tool performance are hardness, toughness, and chemical and thermal stability. Hardness levels correlate to abrasion wear resistance to the tool and this primarily affects flank wear. Toughness indicates the tool's ability to withstand high cutting forces and impact loading caused by interrupted cuts and this affects tool edge fracturing and chipping. Chemical stability relates to the tool's chemical wear resistance by diffusion or dissolution and this affects primarily the rate of edge cratering. Thermal stability relates to thermal shock resistance or resistance to thermal cracking.

Combating these types of wear for turning, milling and grinding processes have been accomplished by designing polycrystallic cubic boron nitride (CBN) inserts with specific microstructure compositions which include ceramic particles.

Simultaneously, there has been the development of materials, such as tough alloys, ceramics and reinforced plastics, which are difficult to machine. Consequently, the accepted theories and procedures for machining have to be modified in order to predict tool efficiency, tool life and fracture in modern operations. In addition, new methods of data collection for the monitoring and control of modern machine tools have become necessary. These developments obviously have an important bearing on machining costs.

Justifying continuous monitoring of a machining process depends heavily on the quality required from the process and the operation plans. Clearly, the reliance on such monitoring could be significantly reduced if accurate models or theories for calculating tool settings and machining times were available. Pending such availability, monitoring of machining operations will continue to be very critical for achieving exact tolerances.

2.0 COMPONENTS OF A MONITORING AND CONTROL SYSTEM

The components of a monitoring and control [5] system is shown in Figure 1. The utilization of sensors as feedback elements for unmanned machining indicates that the development of reliable and effective sensors for monitoring machining operations is necessary. These sensors are required to ensure sufficient metal removal rates and taking corrective action in the event of unforeseen occurrences. The main components are described below.

2.1. *Sensors*

Sensors are used to monitor and measure the physical state of a process variable such as speed, displacement, force and temperature. The functioning of sensors are basis on physical properties such as changes in length and electric resistance. Their application could be direct or indirect, post process or in-process continuous or intermittent. Intelligent sensors could be used for signal processing and conditioning.

Examples of sensor application include the use of an inductosyn and photo-tachogenerator for position and speed monitoring. Intelligent sensors used in Torque Controlled Machining (TCM) monitoring consist of a microprocessor with additional circuitry to conduct computations, and to communicate with the machine tool controller.

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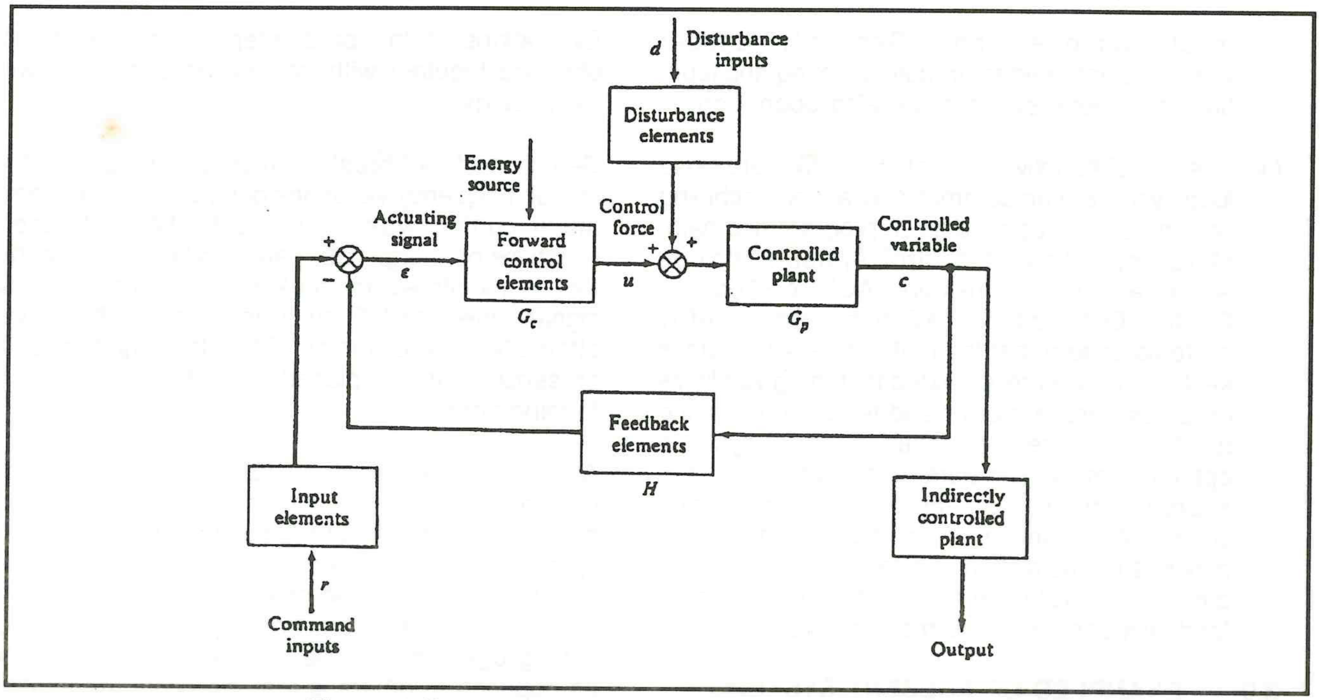

Figure 1 Components of a monitoring and control system

2.2 *Models*

Models can be classified as mathematical descriptions of a system. They are necessary to relate the measured sensor output to the performance of the tool or variable being monitored or controlled. They can be either physically or empirically based and can be categorized as follows:

(i) Fixed Models, which require fixed parameters to be inputted before operation. The model parameters are time invariant.

(ii) Adaptive Models, which allow parameters to be modified as data becomes available continuously or intermittently. An example of such a model is control of spindle speed of a machine tool as spindle motor power sensors provide digital inputs to a microprocessor for evaluation of motor drive power and torque.

(iii) Self Learning Models, which can adapt on the basis of their own observations, according to some definite programmed path, such as maintaining optimum tool life.

(iv) Multi Model System, in which a number of interacting models are used. The general performance depends on the interaction between these models. An example of such a system is a "Power Monitor" device manufactured by Valeron Digital Techniques Division. The monitor senses the current, voltage and power factor of the spindle motor and evaluates the power consumption. Interactive models provide the adaptive control and hence machine overload protection.

2.3 *Signal Conditioning*

This process condenses information in order to extract the relevant data. As a result, the signals are amplified, filtered or A/D converted and selected. Quite often, the power spectral density of a signal is required, using digital methods from a discrete time series representation of the signal. Generally, Fast Fourier Transform (FFT) algorithms and FFT analyzers are utilized for spectral density plots for analogue signals. Other methods include special purpose software such as Lab Windows 2.3, developed by National Instruments Company which allows digital signal processing, data acquisition, control of process variables and virtual instrumentation.

2.4 *Process Operation*

The final link in the monitoring system is the process operation which can be a combination of the following operations.

(i) The measurement of the conditions of a machine tool or process intermittently or continuously and to present a display or annunciation status. Consequently, guidance is provided to the operator for any intervention required. For example, a lubricating oil level alarm in the event of a low level. These operations are open loop since the controller does not utilize the output signal from the process operation for any interaction or corrective measures to be undertaken.

(ii) The use of Diagnostic Systems which could assist in determining the cause of an interrupted machining operation. Generally, Ladder Diagrams are used for trouble shooting and fault-finding. These systems are also open loop.

(iii) The use of Adaptive Control (AC) which are close loop systems, can automatically adapt machining parameters based on a given programmed path. More sophisticated control systems include Adaptive Control Constraint (ACC) or Adaptive Control Optimization (ACO) systems. ACC systems ensure that the material removal rate is kept at a maximum, provided that the given limits of forces, torque, power and temperature of the machine tool are not exceeded. ACO systems optimizes machining parameters with respect to a programmed target of minimum machining costs. An example of an AC system control action is the activation of a feed stop in event of a machine part failure such as the servodriver or feedback sensor of the machine tool.

3.0 EXAMPLES OF PRESENT SYSTEMS

Various types of monitoring and control systems have been derived for detection of tool wear [9, 21, 6], and for tool chipping and breakage [7, 12, 22]. For the tool wear process, methods utilizing in-process monitoring by the Frequency Band-Energy Method [9], resulted in the early correct predictions of rapid tool wear, thus allowing adequate measures to be taken to prevent workpiece and tool damage. Another method by [6] utilized image analysis of a worn tool. Flank wear was observed using a fiber optic system by laser lighting. From the image, the position and dimensions of the crater was possible. Evaluations of the parameters of tool wear were obtained together with information about tool wear morphology.

Detection of tool break by monitoring the amplitude of high frequency vibrations generated during normal metal cutting was achieved by [7]. Ultrasonic vibrations or energy (UE) generated from the machine tool is monitored for took break. The frequency signals used for UE analysis do not suffer severe attenuation and distortion. Therefore, the transducer or sensor can be placed fairly far from the chip forming zone.

Another development by [22] using a multi-edge cutting tool presented a monitoring method for tool breakage by means of the fluctuation signals of the spindle rotational speed. These fluctuation signals give information on the change in the pattern of the cutting torque due to tool breakage during intermittent cutting operations. The superiority of this method as opposed to others is that it reflects the variation of the cutting torque without being contaminated by noise from the power source frequencies. Normally, spindle motor current is used to determine variations of cutting torque and hence tool breakage. However, noise from the power source contained in the motor current signals prevents the extraction of the torque variation signal, when the cutter frequency approaches the power source frequency.

The use of Acoustic Emission Sensors (AES) by [13, 21, 8] for the detection of tool chipping and wear provided quite suitable for turning, milling,

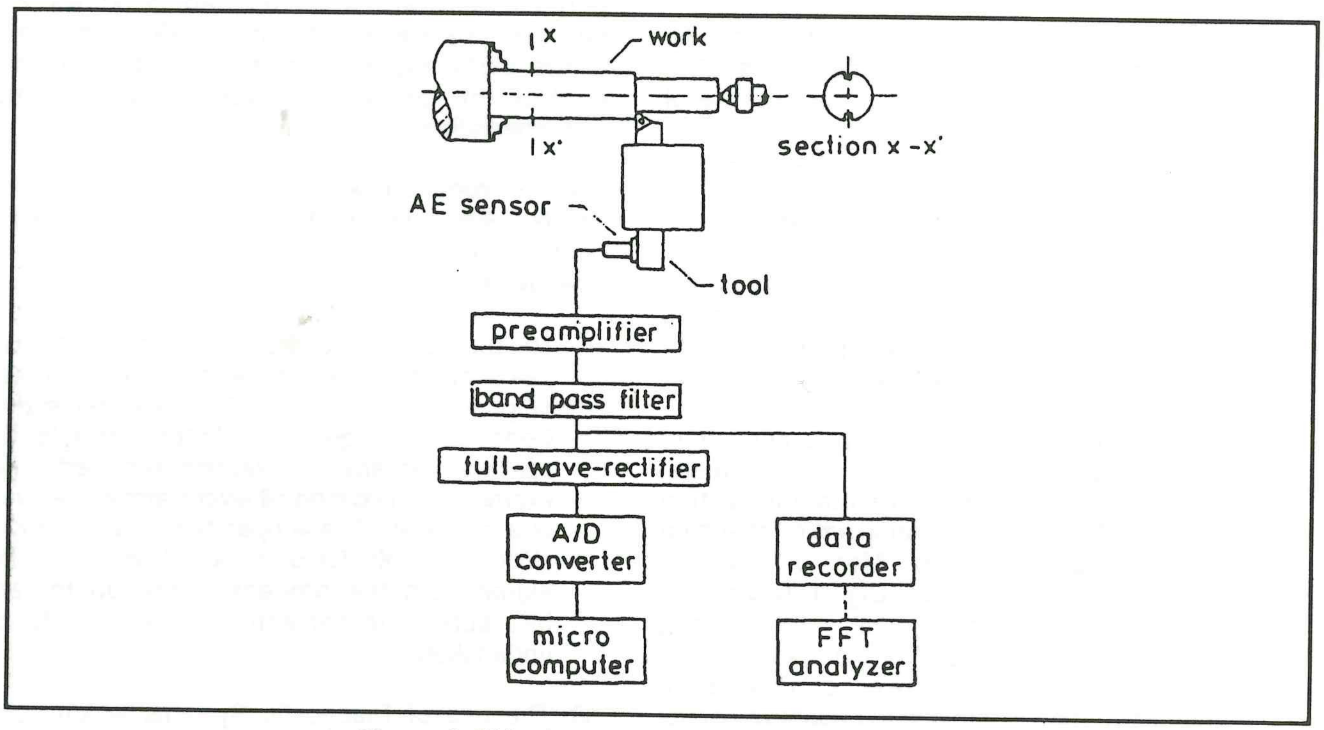

Figure 2 Chip detection of a single point cutting tool

drilling and high speed milling. The principle used the acoustic energy generated during the wear process during cutting, Figure 2, which are detectable. Separation of the microscopic acoustic signal from the complex acoustic noise is difficult since there is no technical means of isolation. Be measuring the force components and vibration signals on the workpiece and tool holder, and the spindle power, specific changes in these measured variables were correlated with corresponding cutting events observed with a video system. Consequently, [13, 8] showed that a dependable relationship between net power consumed for cutting, the corresponding AE signal, and the mechanical parameters of cutting can be derived.

An investigation into the chip formation process by [14] revealed that a relationship exist between the chip formation process and the dynamic cutting forces in the shear zone. The study involved measuring of these forces with a conventional accelerometer and an enhanced force sensor for measuring dynamic forces from the insert. The force sensor was placed between the insert and the shim. Using FFT analysis of the signals from the sensors, the transfer function of the system was determined. Furthermore, metalographic chip samples were taken so that the segmentation frequency in the chip forming process can be derived. These frequencies were compared to the frequency analysis from the transducers. Consequently, a more comprehensive formulation of chip formation was established.

Further developments by [10] employed the principles of a modern RADAR called SODAR, Sound Detection and Ranging to detect the size and velocity of an object. SODAR uses sound waves instead of electromagnetic waves. Chip formation may be classified into two groups. Firstly, the broken chips leaving the cutting point at a relatively constant velocity at a fairly stationary direction. Secondly, the chip breaking is discontinuous and are formed into spirals, tangles. They are observed to move at a much slower speed in random directions.

By utilizing SODAR, [10] demonstrated that this chip control monitoring system to detect the chip form can be applied where there is a risk of changing machining tool parameters. These parameters include tool wear, variations in work material properties, and the like. Consequently, unattended or stand-alone machining, and early detection of tool damages to tool and workpiece, as well as breakdowns can be executed.

Another monitoring and control type shown in Figure 3, deals with the use of Cepstrum Analysis, a method developed by [2]. Cepstrum Analysis is a method for the deconvolution of signals. The model parameters, which are time dependent can be evaluated from this analysis once the output variable is known. This allows comparison between the model

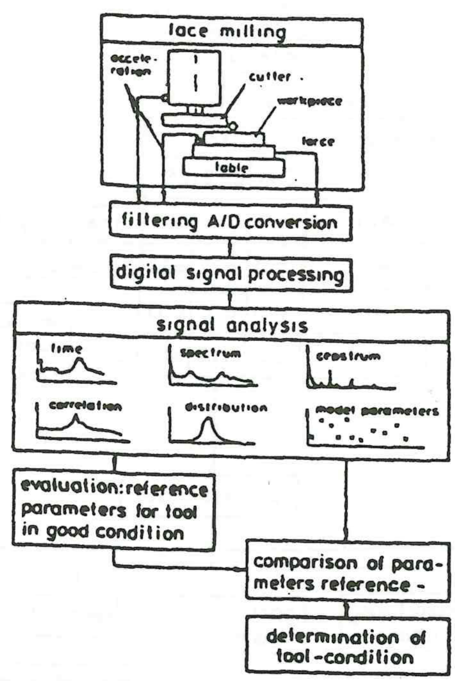

Figure 3 Tool breakage detection in face milling using Cepstrum Analysis

and input parameters which are also time variants. This method proved to be quite effective where workpiece geometry is complex and ceramic inserts are used.

Another system for the monitoring and control of a grinding cycle, developed by [16], permits a practical method known as Adaptive Control Optimization (ACO) for grinding operations. The optimization strategy utilizes off-line procedures in an interactive mode with a microcomputer. The grinding and final cut parameters are input to the computer together with a suggested set of trial operating parameters. By repeating this optimization procedure with continued grinding, the grinding and final-cut variables converge toward the optimal operating set. These optimum operating parameters are then stored in computer memory for the next task.

4.0 ENHANCED STRATEGIES

Enhanced control strategies can be categorized into three sub-systems namely:

(i) Learning and decision making systems

(ii) Rule-Based systems

(iii) Error Diagnosis and Recovery Systems

A learning system is one in which information about the unknown features of a process or its environment is acquired by the system. The obtained experience is used for future estimation, recognition, classification, decision or control to improve the performance of the system.

The structure of a learning system consists of the supervised object (machine tool, workpiece, machining process), the reference, the correction and learning and the teaching sub-systems. The determination of relevant conditions require the use of sensors, mathematical models and signal conditioning equipment. Generally, with conventional systems, a deviation between actual and desired values in nullified by adjustment of the control variable. The process of adjustment in learning systems however, is more complex. The aim of the learning system is to make a control algorithm as adaptable as possible to the actual process conditions. The variables to be adjusted include not only the control strategy, the control algorithms and the models which are applied. This means, therefore, that the reference system which delivers the required outputs has to be initially preconditioned. The reference system may be a direct measured value or obtained from an operator's knowledge or reliable source.

The Teaching System compares the measured process variables with those values of the reference system. Recommendations are now given by the teaching system on the adjustments to be made by

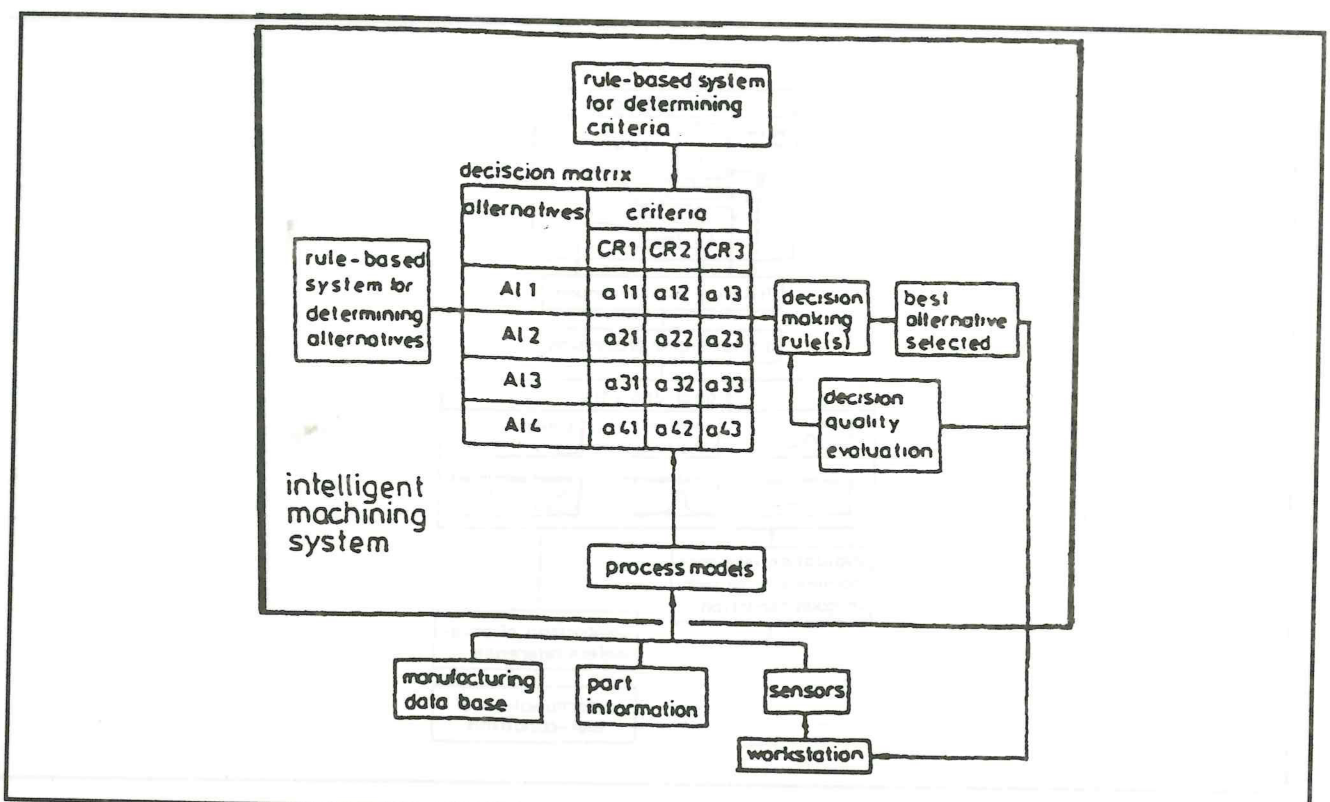

Figure 4 Basic structure of an intelligent machining system

the adaptive and learning system whose variables have to be changed. Adaptive Learning Control will be much more utilized with the increasing reliability of reference systems, and the experience of its end-users.

Figure 4 shows the layout of a Rule-Based intelligent decision making system for the control of CNC machining processes. The major difference between the automatic and intelligent workstations is that the intelligent system is capable of making decisions based on significant data about the state of the system. Techniques developed by [4, 19, 3] showed that the decision making method can be expressed concisely in a decision matrix type of format. The matrix elements of the matrix indicate that evaluation of each possible alternative with respect to some initial pre-conditioned criterion. An example of such a system is itemized below:

(i) The criterion is to guarantee safe and reliable machining operations.

(ii) The matrix elements consisting of a number of hazardous events such as tool wear, vibration, excessive temperature and other machine failures.

(iii) The decision matrix which evaluates the events in case of occurrence and thus derives the alternatives for further evaluation.

(iv) Evaluation of the alternatives results in adequate response within milliseconds, satisfying in initial criterion.

This approach allows decisions to be made quickly within the time frame required by an intelligent machining workstation. Figure 5 illustrates the structure of this type of model in greater detail.

The third sub-system, based on recovery strategies, is absolutely necessary for automatic problem diagnostics and automatic restart of CNC machining processes. One of the objectives is to decrease the non-productive time of a machine tool after a failure has occurred. This system contains all relevant information in a process, a step by step procedure of events, as well as a history of previous operations stored in a computerized file or log book. The operations durations must be long enough to be able to re-construct the cause of the failure. Signals obtained by sensors, which may be binary or A/D converted, are evaluated and stored in a buffer. The stored information is continuously updated with new readings from the sensors. Upon test simulation or actual failure, the range of values belonging to the respective measured quantities up to the instant of process breakdown is now compared with know histories of possible failures. Determination of the origin of the breakdown is now conducted by failure analysis. Note that the system may or may not recover from its failure.

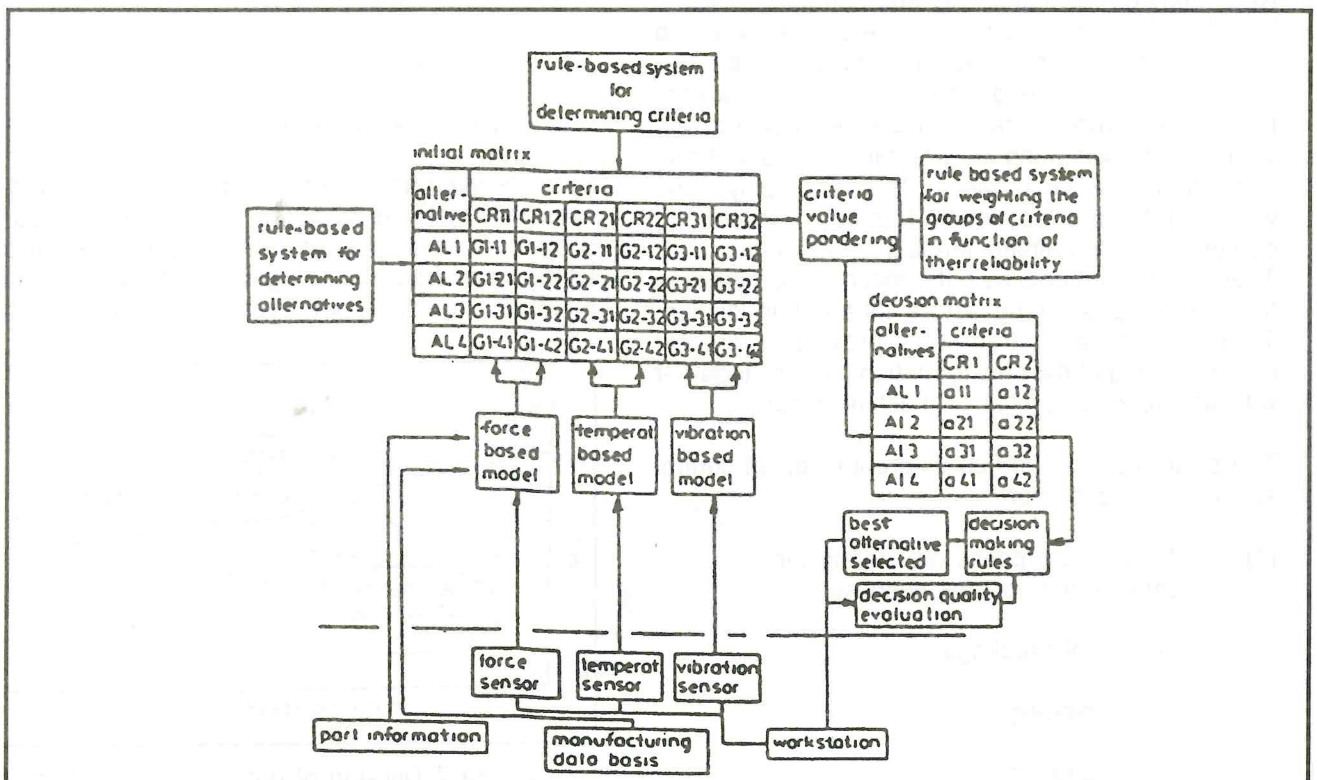

Figure 5 Detailed example of an intelligent machining system

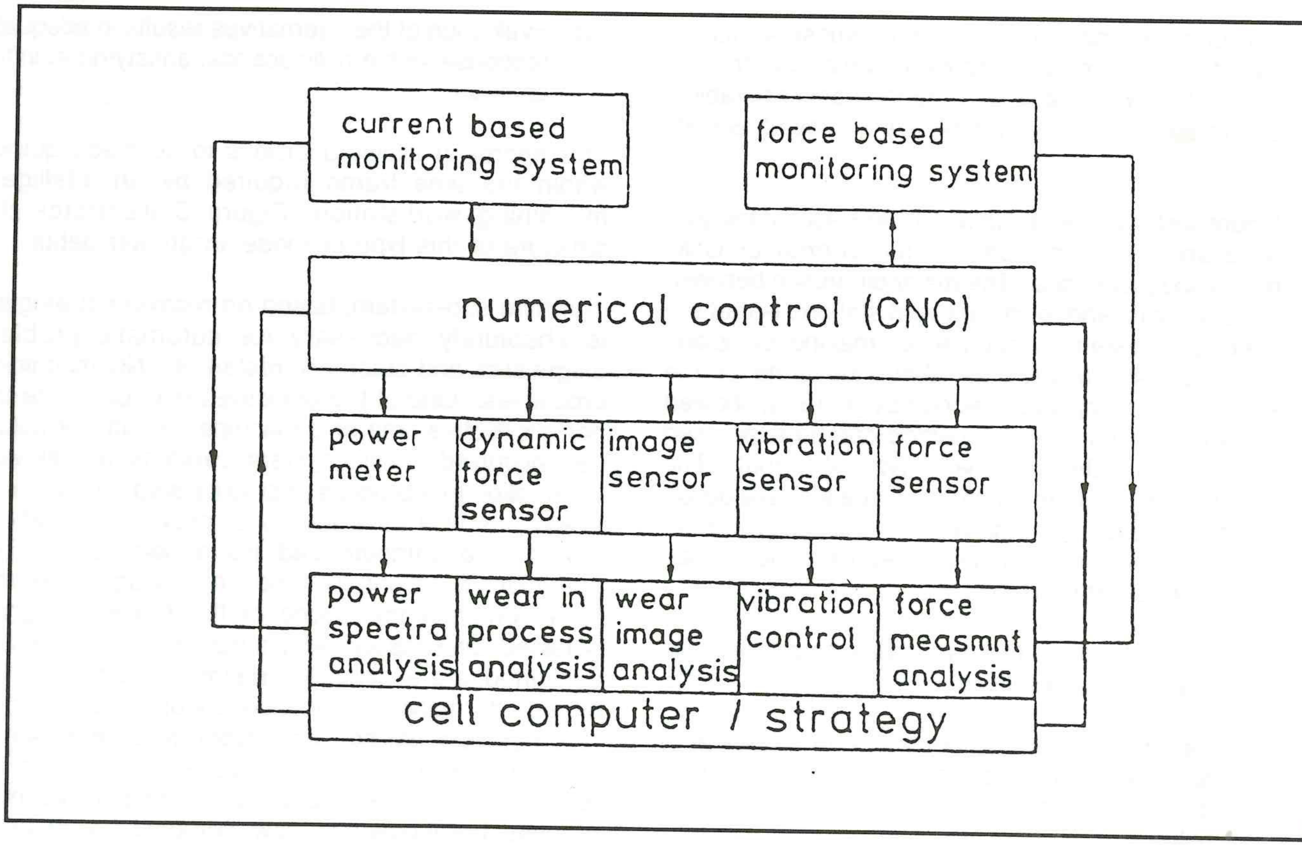

Figure 6 Example of a "Multi sensor/model system"

5.0 FUTURE TRENDS

New methods for monitoring and control are based on "Multi-Sensor Systems", Figure 6, give extended characteristics of the machining parameters. For example, the monitoring of the cutting tool vibrations, forces and temperature can be superimposed with intermittent monitoring or workpiece surface finish using touch trigger probes. This is suitably done with spindle probes which transform machining centers into Coordinate Measuring Machines [11]. These measurements help the machine compensate for internal positioning errors inherent in design. These measured parameters provide a greater understanding of the chip formation process together with an improved profile of machining data.

The system described has different levels of control and monitoring namely:

(1) Advanced process monitoring for catastrophic failures such as,

- (i) tool breakage
- (ii) chipping
- (iii) vibration

(2) Adaptive Control Constraint (ACC) with feedback applied to,

- (i) control of forces
- (ii) control of vibration

Systems such as the foregoing can be classified as intelligent modules because they are controlled by computers employing real time techniques. It can be deduced from the foregoing that the application of Multi Sensor/Model Systems to machine tool

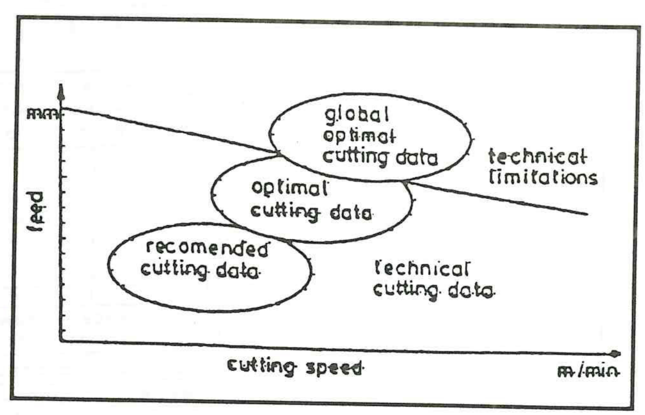

Figure 7 Division of data types in cutting

operation will become more utilized in newer machines.

In conjunction with these improved systems, new cutting data must be applied for optimum machining operations to be achieved. Cutting data as categorized by [15], in Figure 7, which can be successfully applied where only specific technical limitations are taken into account is called Technical Cutting Data (TCD). The standard Recommended Cutting Data (RCD), currently used in industry [18,1] are rather conservative and could consequently be uneconomic. Cutting data which utilizes both economic and technical limitations with respect to specific conditions are referred to as Optimum Cutting Data (OCD). Most systems deal with RCD, and therefore in order for ACO to be successful in future machine tools, OCD has to be researched and implemented together with an update of basic cutting data for future applications.

Another development by [23] is a monitoring and control system for internal grinding which uses a microcomputer for force control.z The advantages of this system are:

(i) 'First cut' detection during approach rates up to 10 mm/sec.

(ii) Decrease in overall grinding time.

(iii) Optimum reduction of non-circular grinding.

(iv) Off-line control in order to tune the control algorithm.

(v) Increased safety when using vitrified bonded BN wheels.

Figure 8 shows the grinded forces associated with different types of process control. The feed rate is actuated through CNC, and the correct grinding force has to be attained in the shortest possible time. Figure 9 shows the hardware set-up for the digital control loop for internal grinding. The type of supervision is Adaptive Control, and the variables are the normal grinding force and the grinding spindle input power. The grinding forces is measured with a peizoelectric dynamometer beneath the spindle. This sensor measures a wide frequency range in order that high approaching feed rates can be executed.

Power measurement causes a dead time which must be accounted for by the control algorithm. A deadbeat controller is utilized to offset the dead time. This controller allows the output to reach the reference command in a minimum of discrete sampling time period of the controlled variable. A powerful microcomputer, utilizing the thirty-two bit microprocessor permits programming in PEARL

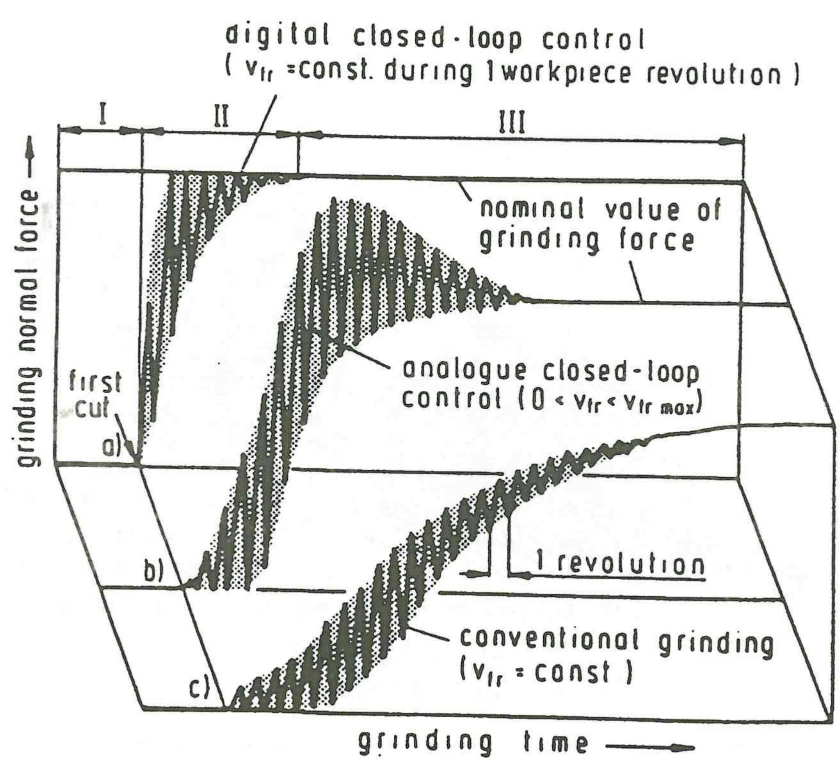

Figure 8 Grinding force/time relationship using various types of process control

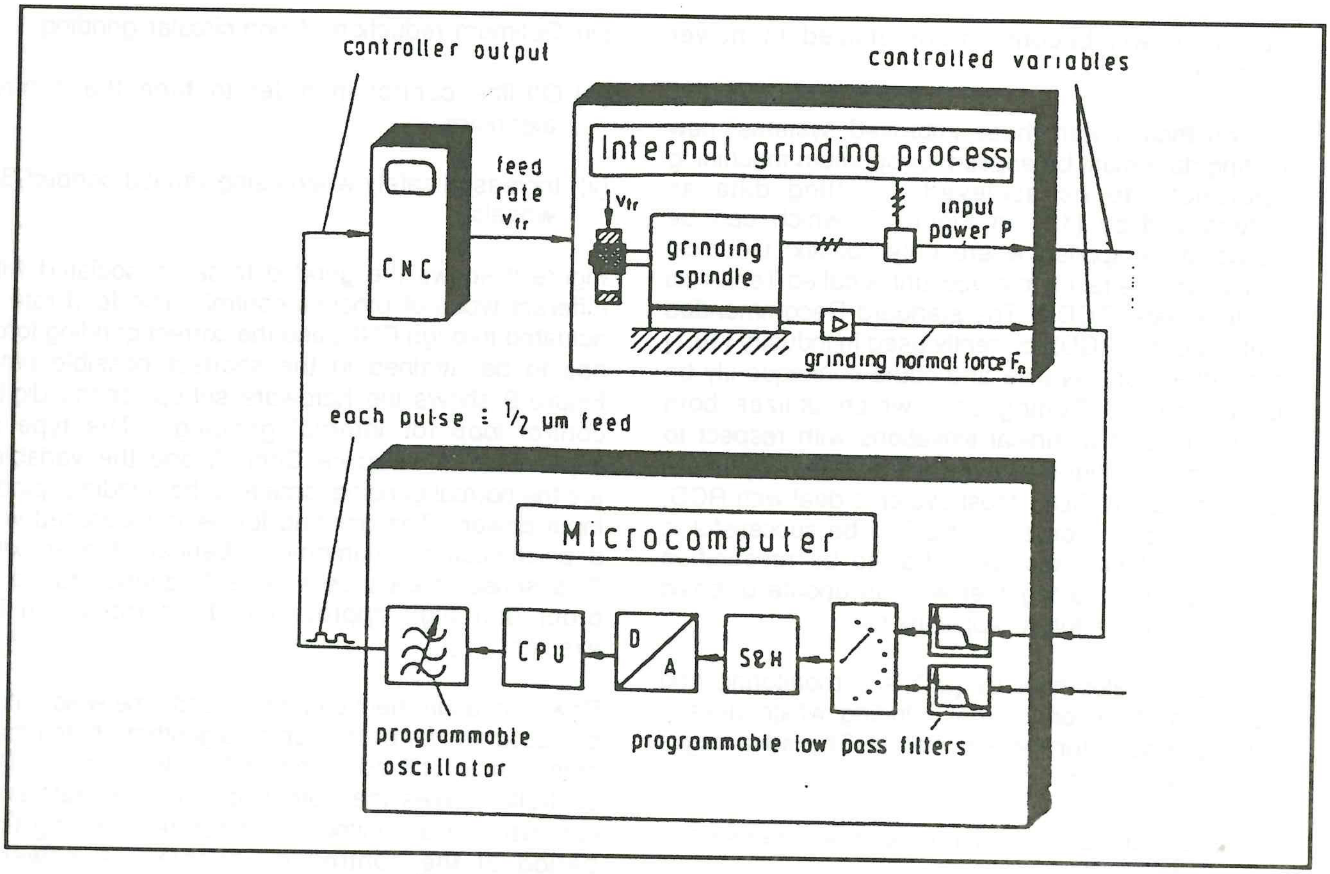

Figure 9 Control loop for internal grinding

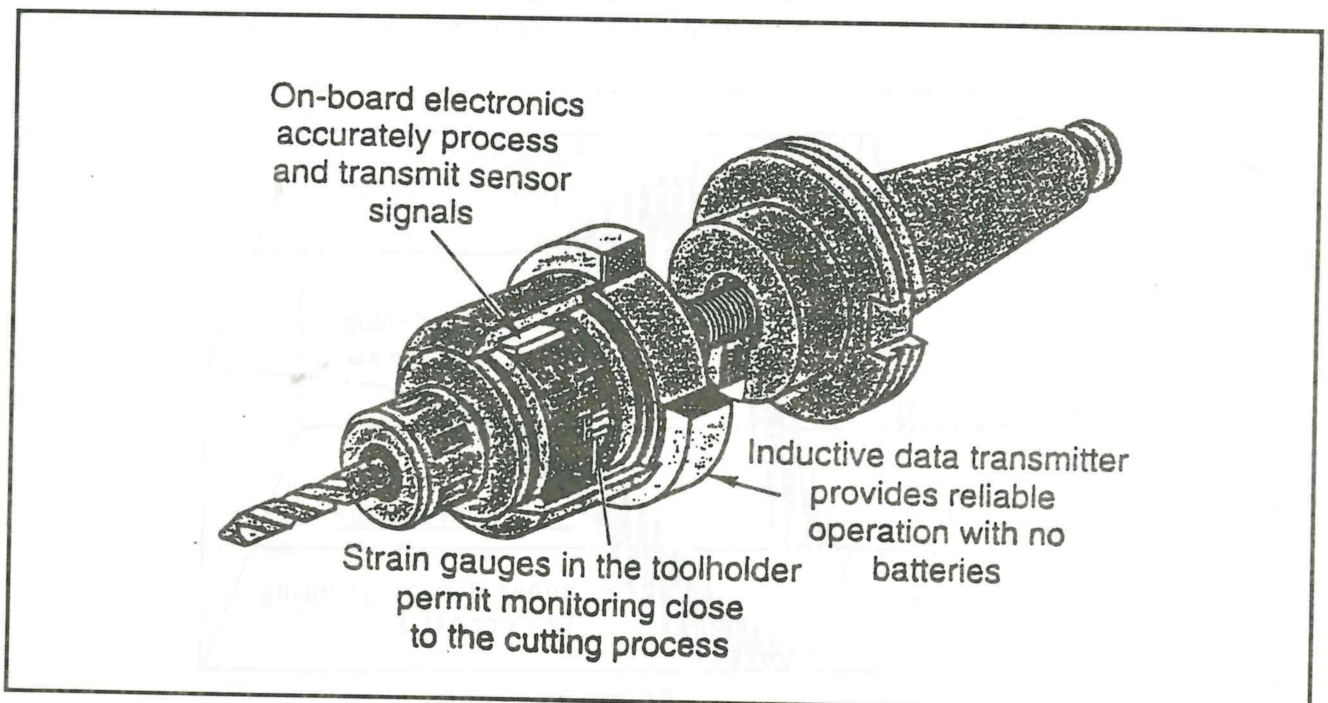

Figure 10 Intelligent intellitool rotating tool sensor

(Process and Experiment Automation Real time Language). The programming language PEARL is used for the development and testing process identification and digital control. Fast A/D converters are used for quick response to the first cut process. Programmable low pass filters are employed for different sampling frequencies in the distinct phases.

Sensor implementation to tool holders, a recent innovation developed by Sandvik Automation [20], utilizes strain gage sensors and on-board electronics to process and transmit the sensor signals. These "Intellectool Rotating Tool Sensors" developed by Sandvik Automation, Figure 10, enables the machining centre to react automatically and reliably to worn or broken tool conditions. The advantage of this system as machine tools adopt this configuration is that is allows easy tool holder retrofits, requiring no costly dismantling and refitting.

The future trend for five axis milling centers is its increased flexibility and user friendly functions. The Mazak Versatech V-40 five axis center, [17] can switch between a horizontal and a vertical spindle in 17.9 seconds. The control software provides a plane conversion function, adjusting the x-y-z reference for each spindle. Therefore, the operator can machine using the same x-y-z- coordinate system for either spindle.

To reduce programming time, the control system allows the operator to input data conversationally. It then automatically determines the optimum toolpath and cutting conditions based on the tool, workpiece material and machining shape.

6.0 DISCUSSION

In the Caribbean, CNC machine tools have been implemented over the past fifteen years with its earliest utilization in the manufacturing sector. This duration is by no means lengthy and therefore the adoption of this technology is in its developmental stage. The role of the Engineering Faculty at the University of the West Indies (UWI), as a leader in this new technology, is based on several key issues which are required for its technological growth.

With the available infrastructure at the UWI, which includes machining and support software packages and CNC machine tools, dedicated and skilled operators are required for precise and efficient machining of complex parts. These operations and methodologies which are performed by the operator or engineer must be exact and can only be attained by experience.

Within the Caribbean manufacturing sector, the use of CNC machine tools will increase as manufacturers have to become more competitive worldwide in order to reduce product costs and improve design flexibility. The role of the Engineering faculty and its CNC resources as a training center for engineers and operators is vital in order to facilitate this need,

Product design and development must be an integral part of the UWI machining center in collaboration with the manufacturing industries. This will facilitate research programs and stimulate manufacturing.

7.0 CONCLUSIONS

The need for monitoring and control of machining operations cannot be overlooked since the homogeneity and predictability of work materials and tool materials are variable. As a result, the great dependency on Adaptive Control (AC) utilizing optimum machining parameters is critical for maximum tool life and minimum tool failures.

OCD which has to be utilized by CNC machine operators can only be developed if sensor-based monitoring of machining operations are conducted. This involves the setting up of AC systems which allow operators to be more predictable about tool life and surface finish of components. Consequently, local appliers of CNC technology in the Caribbean must adopt AC techniques in order to attain maximum tool life and lower production costs. Consequently, OCD can now then be derived and continually upgraded for optimal machining operations.

Although AE sensors have been successfully demonstrated in laboratories, it has not yet found wide acceptance in industry. A great deal of on-site tuning of these sensors seems to e needed. When one considers the aerospace industry, machining these tough alloys produce intense temperatures and stresses at the tool edge. The use of sensors ensure part dimensions are exact.

Non-tactile sensors such as machine vision are yet to be fully exploited for monitoring cutting operations such as checking tool wear between processes. When finer resolutions are required about surface finish, machine vision may provide an alternative to touch-trigger probes for dimensional measurement.

Future work must be devoted to the refinement of those existing sensors. However, the issues to be looked at must include not only new sensor development, but also the ability to use present sensors more conclusively in order to understand the principles of chip formation.

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