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FLEXIBLE EXPERT SYSTEM FOR AUTOMATED ON-LINE DIAGNOSIS OF TOOL CONDITION

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Abstract: An increasing number of Flexible Manufacturing Systems (FMS) have been installed in Europe during the past few years. The general experience is that the availability of the FMS is not as high as was originally expected and especially their unmanned use during three shifts has not been successful. One of the major problems is the deterioration or failure of the tools. To develop a system to address this, a wide cutting test and analysis program for tool wear was performed. The test program covered both shank end and end mills together with twist drills and tread taps. For monitoring the tool wear a number of monitoring methods such as vibration, acoustic emission, sound, spindle power and current, axial force, torque were tested. The relations between the analysed signals and tool wear form a basis for the diagnosis rules that are used in an diagnostic expert system module. An expert system for automated on-line diagnosis of tool wear of different types of tools was built using a new approach. In this approach the faults are described in a fault tree database and the corresponding features of condition monitoring signals together with the machine status information are described in a symptom tree database. Using a rule synthesiser program the information gathered in the databases is automatically converted to expert system code.

Key Words: Artificial intelligence, Condition monitoring, Expert systems, Flexible manufacturing systems, Tool wear monitoring

INTRODUCTION. An increasing number of Flexible Manufacturing Systems (FMS) have been installed in Europe during the past few years. A general experience is that the availability of the installed FMS is not as high as was originally expected, and especially the unmanned use has not been successful [1]. A major problem is the condition of the tool. One of the most important reasons for this is today's existing real-time tool condition monitoring techniques do not cover the wide range of different machining situations and machining parameters that normally take place in practice.

There is a need to group and synchronize sensor signals together to avoid poor correlation between a single signal source and the measured event. However, it is obvious that the commercially available monitoring systems are exploiting just a limited number of the capabilities of modern sensor and analyzing techniques [2]. In this survey several sensors were installed and comprehensive laboratory tests done before the concluding sensor validation [3]. The aim was to accomplish the requirements of condition monitoring at critical points of the machine tool and in the cutting processes. The validation was performed according to the following criteria: sensitivity of the sensor to the measured event, correlation between the signal and measured event, the amount of deviation and universality. The information received from multiple sensors was analyzed with many different methods. The relations between the analyzed signals and wear form a basis for the diagnosis rules that can be used in an AI system.

The diagnosis of the condition monitoring signals has to be done using an expert system since the goal is to be able to use FM-systems unmanned in three shifts. One big problem in reaching this goal is how much the FM-systems differ from each other. From this it follows that an expert system should be easy to configure for each task. Unfortunately, the behavior of measuring signals is a function of the machine tool and tool type. In this study a lot of emphasis has been put on creating a generic solution, and a new approach to configuring an expert system. The basic idea is to use databases for defining the varying information, and to use specific software to write the expert system code automatically. The user only defines the necessary data with the aid of modern tools for database handling and the computer translates that information into a working expert system code.

TEST ARRANGEMENT. A small horizontal-type machining center with an 11 kW main motor power was used in the cutting tests for tool and machine tool condition monitoring. The tests concentrated on tool wear, tool breakage and collision monitoring. Cutting tests were performed in order to create situations where a measurable event was present due to tool wear or failure. In this part of the cutting tests, different types of cutting tools were used to cover a wide range of different cutting methods. The tools investigated in the tests were shank end mill (diameter 6 and 10 mm, HSS), end mill (diameter 50 mm with carbide inserts), twist drill (diameter 3.3, 5.0, 6.8, 8.5 and 10.2 mm, HSS) and thread tap (M4, M6, M8 and M12, HSS). The tool-monitoring tests were carried out by using different kinds of measuring arrangements. The main configuration of the measuring arrangement can be seen in Figure 1. A more detailed description of the measuring arrangement is in reference [3].

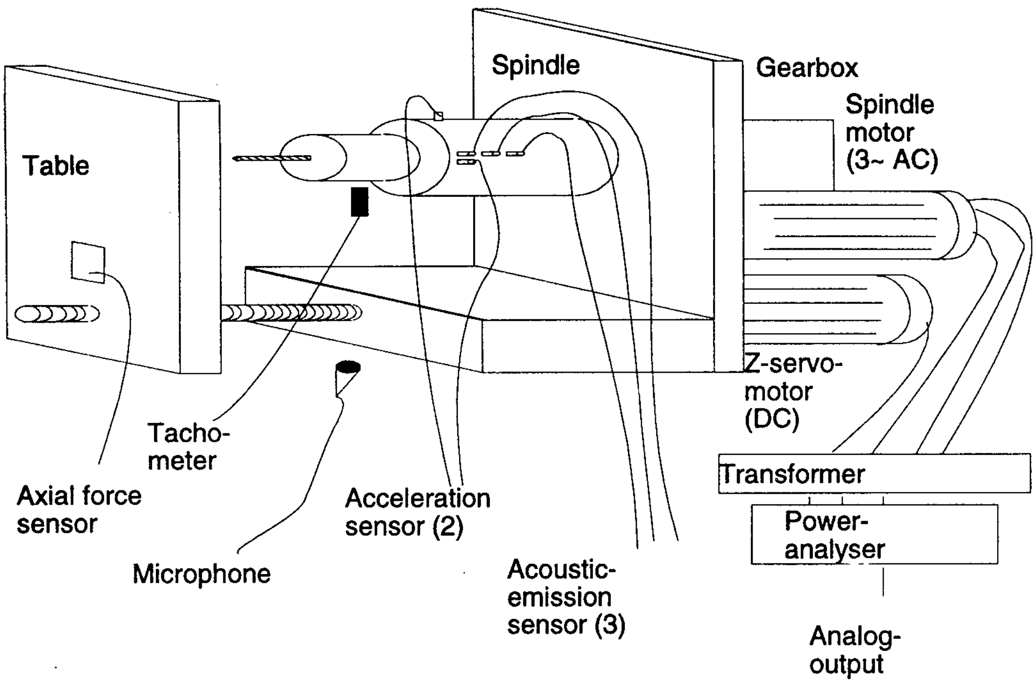

Figure 1. Measuring arrangement

EXPERT SYSTEM. With the increasing complexity of NC machine tools and flexible manufacturing systems, and with the growth in diversity of systems, it is increasingly difficult for maintenance personnel to assess the problems rapidly. Long delays in identifying the precise problem greatly increases downtime and causes even bigger secondary problems in plants. This is especially true for FM systems where the material flow from a machine tool to another is performed quickly with a minimum number of buffers.

To automatically identify the condition of the machine tools and cutting process two types of diagnostics are needed. A reactive diagnosis is needed to identify the cause of a current problem and a predictive diagnosis is needed where ever it is possible to anticipate the need for a maintenance action based on the condition monitoring of the machine tool or cutting process.

The development of a diagnostic expert system is based on diagnostic rules which are derived from the results of the condition monitoring tests. From the results of the analysis it became apparent that rules would become rather complex if the system were completely generic, i.e. suitable for a number of different types of FMS environments, and also that there would be a need to divide the tasks within the system so that responses would be fast enough to perform the diagnosis in the case of collision and tool breakage also.

Principles of the chosen approach. In order to make an expert system flexible and suitable for a wide range of FM systems, a new approach for defining and modifying the rules was developed.

The basic idea is to use the fault tree database definition program for defining the faults, and describe corresponding condition monitoring tools (symptoms) using the symptom tree database definition program. After that, the user starts a rule synthesiser program that translates the contents of the fault and the symptom databases into expert system rule code for the computer performing the monitoring task. In principle the translation program simply takes one page from the symptom tree at a time and writes a module to the expert system code from that. The procedure is shown in Figure 2.

It is considered that there are several advantages to this approach: It is not necessary to write enormous amounts of expert system code manually. It is very easy to make changes or add more information and, especially, it is possible to configure the program for a specific FM-system. Apparently, there are also certain disadvantages to this approach: The amount of code in the final expert system will be considerable since it is not possible to use the sophisticated features of an expert programming package. Instead of a sophisticated system the expert system programming module always writes rather simple modules for each condition defined in the symptom tree.

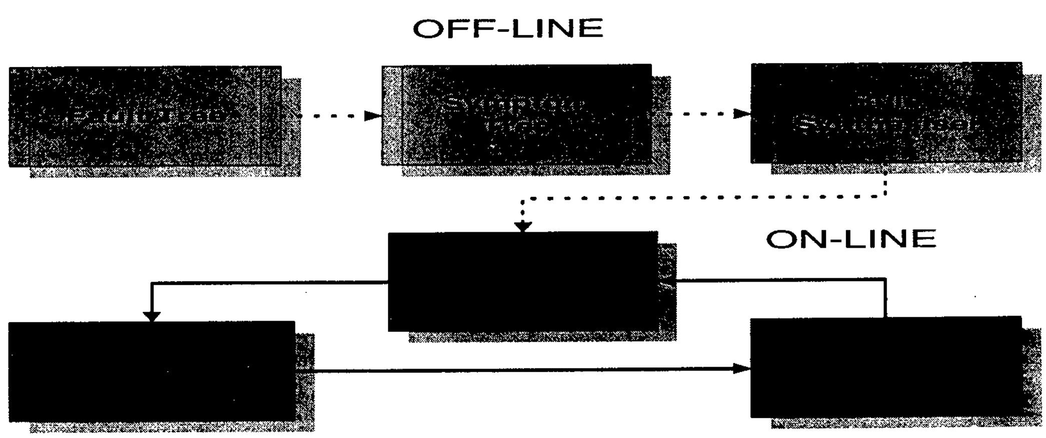

Figure 2 Principles of the new approach to expert system rule generation.

Fault tree. In the fault tree database the machine tool is defined with the chains of subcomponents. The number of subcomponent levels is limited to five. For the lowest level of subcomponents where a principal fault can take place, all the possible faults are described. The fault tree database program has all the typical search and editing functions of a normal database program. The structure/window of the fault tree is shown in an example in Figure **3**.

Symptom tree. Following the definition of all the relevant faults with the fault tree database, the next step in building an expert system with this new approach is to define all the symptoms related to the faults together with information about the machining process. As shown in Figure 4 the following input is defined in the symptom database: fault tree component chain identification, fault to be processed, tool identification, the status information of the machine tool, machining information and condition monitoring method information (symptom). The symptom is defined with signal, general, analysis and limit value information (Figure 4).

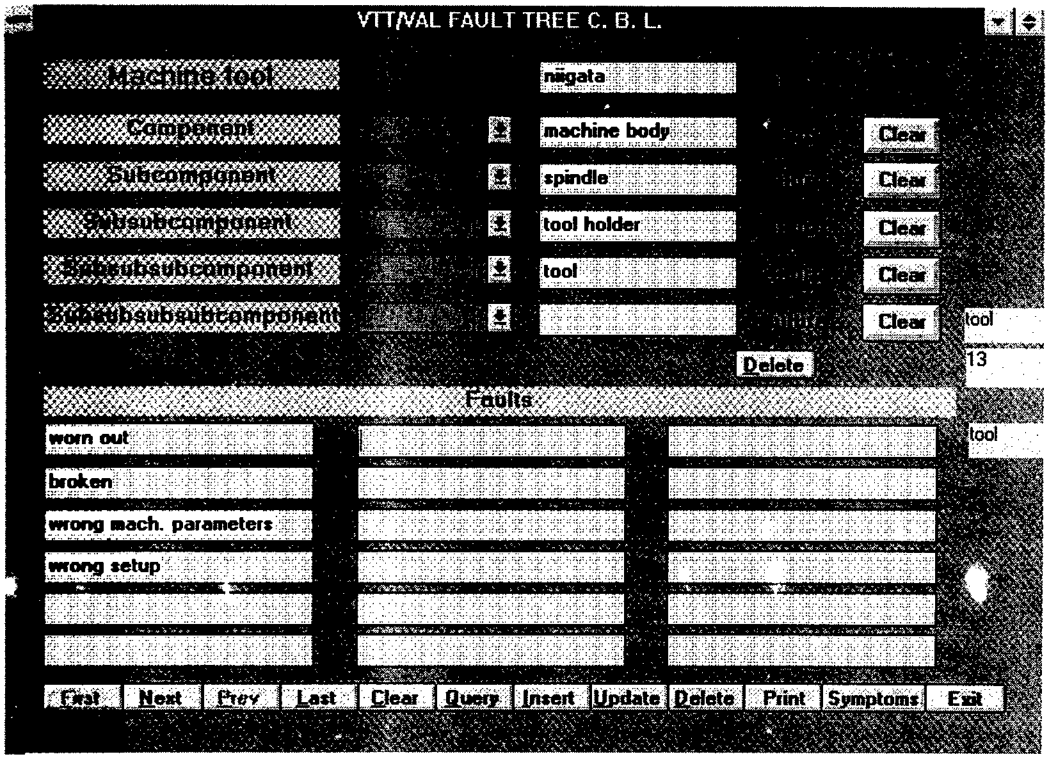

Figure 3. Fault tree database program window

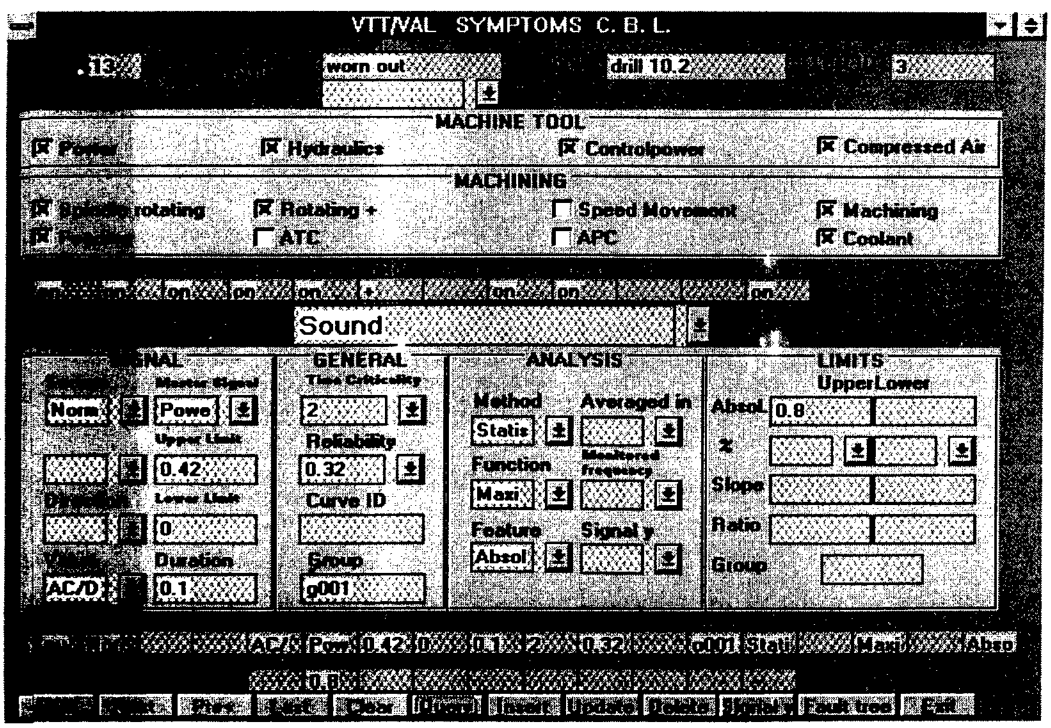

Figure 4. Symptom tree database program window

SIGNAL PROCESSING. For the automatic analysis of the huge amount of data to be gathered an interface was created using the Visual Basic programming environment for Windows. The system gathers the data with a data acquisition board (16 A/D channels, Keithley) and the necessary calculation procedures are defined using a collection of subroutines (VTX) for this AD card family.

Data acquisition. The statistical analysis is based on the acquired data. Attached to the acquisition board, a sample and hold board is used to synchronize dynamic signals. The measured signals are analyzed with a number of different methods in the time domain and in the frequency domain. In the case of dynamic signal analysis, only so-called cursor values are gathered to minimize the amount of information to be stored in the databases. These actions are also controlled by the interface. The flowchart of data acquisition is shown in Figure 5.

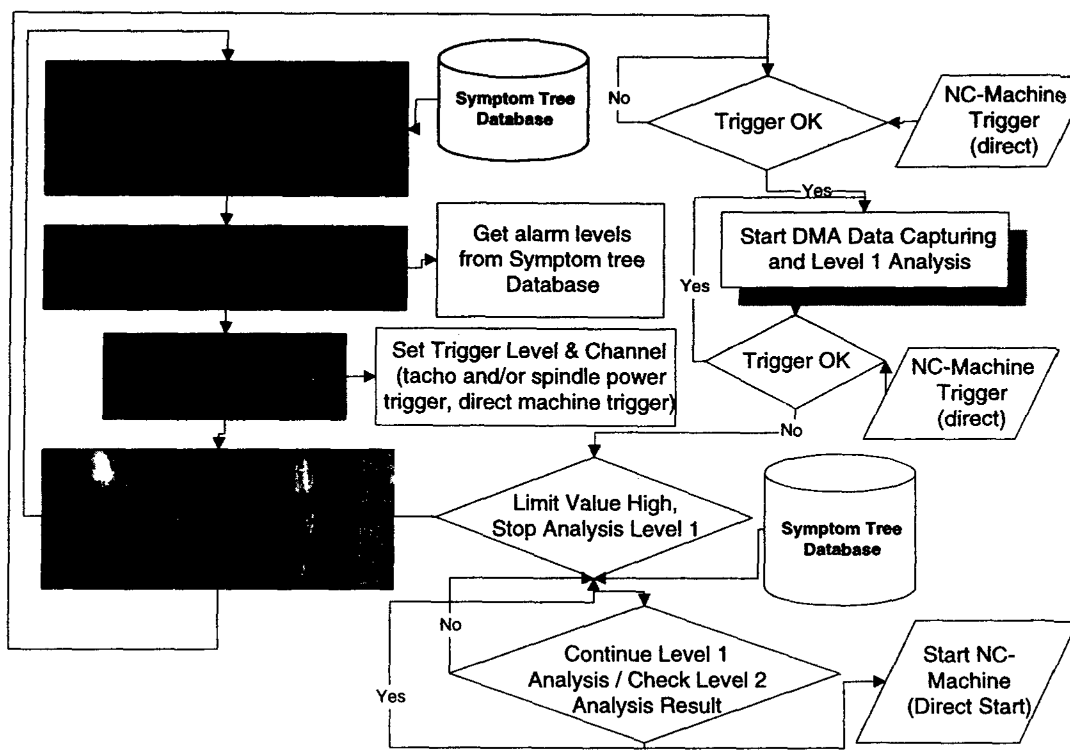

Figure 5. Level 1 data acquisition

Signal analysis. Depending on the measured events, the data to be analyzed is first cleaned of irrelevant signals, e.g., rapid movement during drilling, that has not been recorded during the actual machining process. Data measured and recorded simultaneously from the sensors is studied by calculating a number of statistical parameters: arithmetic mean, root mean square (RMS), mean deviation, standard deviation, skewness, kurtosis, maximum and minimum.

In the case of dynamic signals containing frequency information, Fast Fourier Transformation (FFT) techniques are employed [4]. The sample and hold function of the data acquisition board is used to get data from four channels simultaneously. It is possible to perform a FFT with both time and frequency domain averaging. Different kinds of analysis functions such as spectrum, cross-spectrum, frequency response, coherence, coherent output power, autocorrelation, crosscorrelation, cepstrum, liftered spectrum, 1/3 octave spectrum, 1/1 octave are available.

Regression analysis. The results of the statistical analysis and FFT analyses are further analyzed using regression analysis techniques. Different regression functions were tested to find the highest correlation between measured tool wear and analyzed measurement signals. The sets of data points are approximated as closely as possible with the four smoothing functions [3]: first, second and third order polynomials and one logarithmic function based on a simplified mathematical definition of wear [5] using the least square principle.

The degree of the fit is much higher for cursor values of the FFT functions than for the statistical parameters. This result is logical, since the idea of the FFT analysis is to separate meaningful information from noise. However, it takes time to carry out the FFT analysis, which makes it impossible to use the FFT for collision and tool breakage monitoring but enables tool wear monitoring. The goodness of fit varies with the tool-type. Drilling and shank end milling are the easiest to monitor. Functions describing how much two signals are related to each other, show a rather high goodness of fit (3). The use of at least two signals for tool wear monitoring coincides with the findings of the statistical analysis, since the best methods for monitoring purposes vary between the tool-types.

Simulation module. This work is focused on problems of automatically identifying the condition of the cutting process. The simulation program module is used as a tool to see how the expert system reacts in different kinds of situations with different kinds of limit values for the chosen regression models. The program fits a selected regression curve to the existing data. The fitted curves are the same as those used in the regression analyses. After each time the curve fitting has been done, the program checks to see whether the tool worn-out limit has been reached, giving a warning when the machining process has to be terminated by the expert system. The advantage of using the simulation module together with the regression functions is that with this procedure the amount of measuring data to be stored in the databases is greatly reduced and the method is not too sensitive for sudden changes in the measuring signals i.e. it is possible to avoid most false alarms.

Rule Synthesiser. Knowing what signals to process, how to process them and what features or thresholds to look for after processing, requires considerable knowledge about how tools deteriorate and the signal processing capabilities that are available. This 'expert' knowledge was gained during the initial experimentation of the project. A key facet of the knowledge is the processing to perform changes from tool type to tool type. Like traditional expert systems, a mechanism is needed to allow the expert to naturally specify his knowledge of how to process the signals for a given tool. However, the system cannot use one fixed knowledge base, since the best way to analyze the signals will vary from tool type to tool type. Hence a more flexible approach to building the expert system is needed, since the 'expert system element' will also change from tool type to tool type.

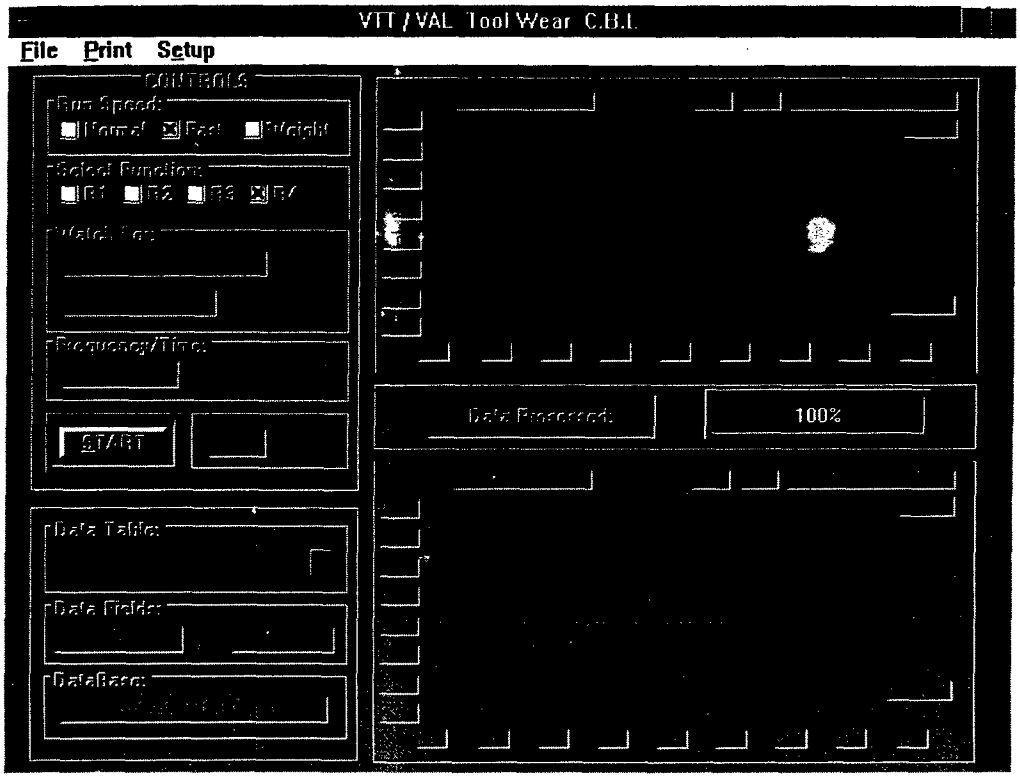

Figure 6. User-interface window of the simulation program, end milling, upper curve: horizontal vibration, mean deviation, lower curve: sound, root mean square

The information in the symptom tree database can be viewed as a specification for the knowledge based rules. Each entry specifies what a rule should look like; what signals to examine, what processing to perform, which features to extract and what thresholds to use. Using a traditional expert system environment would be too complex for experts in this domain to specify all this information. Also, hidden from the expert is the fact that each 'rule' has several parts, corresponding to the above steps. The database front end provides an user interface that is natural for the expert to use and hides this underlying complexity. Our system uses a 'rule synthesiser'. This takes the specification of a rule that is contained in the symptom tree database and automatically generates the computer programs needed to implement these 'rules'. Figure 7 shows the steps and database interactions that result from each rule. Contrasting this with the simple layout of Figure 4, illustrates the gain that results from the use of the rule synthesiser.

The rule synthesiser works by processing each rule specification in the symptom tree database, breaking each rule into several function calls. It also builds the links between these function calls so that the data can progress through the steps of acquisition, signal processing, feature extraction and testing against the specified limits. In addition, it automatically combines rules into groups, for example, all the rules to detect worn out 10.2 mm drills. This process hence implements one of the key ideas of expert systems - let the expert specify the knowledge in a natural way and have the system do all the hard work.

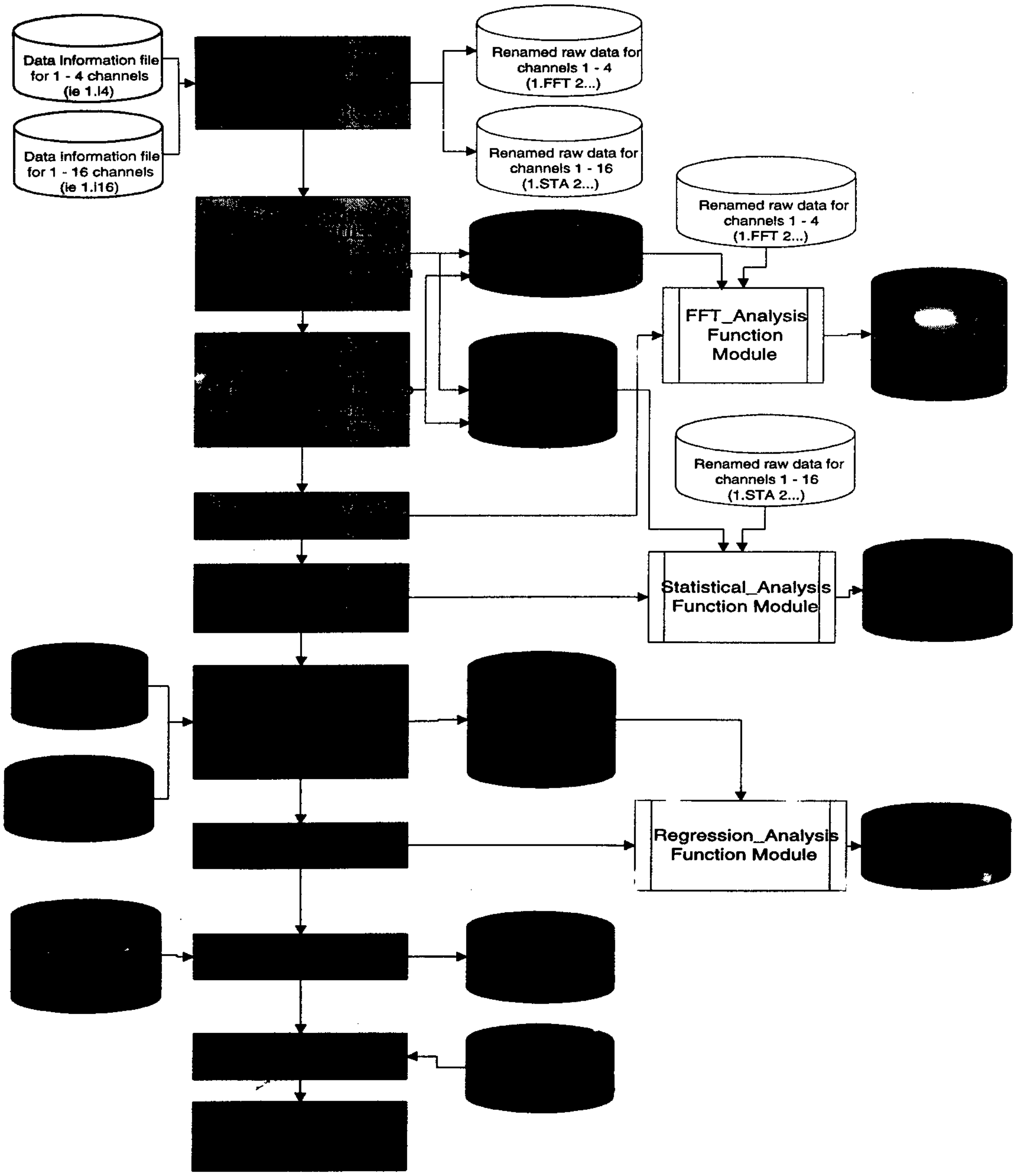

Figure 7. Level 2 rules and data model

CONCLUSION. It has been shown that there exists a great potential to improve the utilization rate of a machine tool by an advanced condition monitoring system using modern sensor and signal-processing techniques. A comprehensive cutting test procedure has been carried out with different tools and measurement arrangements. The recorded signal information has been processed in several ways, both in the time and the frequency domain. The effectiveness of the best sensors and analysis methods have been verified in the prediction of the remaining lifetime of a tool in use. The relations between the analyzed signals and tool wear form a basis for the diagnosis rules that are used in a diagnostic expert system. A new approach to development of a rule-based expert system is reported. The approach makes it easy to configure the expert system for different types of FM-systems with different types of tools. The solution is based on the adoption of fault and symptom tree databases with sophisticated user interfaces for the definition of the relevant fault types together with the corresponding monitoring methods. A rule synthesiser is used to take the specification of a rule and produce the detailed expansion to control the various sub systems of the condition monitoring system. The hides from the expert the underlying complexities of the task and lets him specify knowledge in a way that is natural to him. Without this capability, the system would be too complex to be used by the people who have the appropriate knowledge, and hence the value of the whole system would be greatly reduced. This work has combined extensive laboratory testing with the implementation of a state of the art signal processing environment and an easy to use way to specify the knowledge about how to interpret the data that is collected. Such a system is not only practical, but is an essential part of the how automation can be used to increase the utilization of flexible manufacturing systems.

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REFERENCES.

1. Lakso, T. The Influence of FMS-techonology on the Efficiency of NC-controlled Machine Tools. Tampere University of Technology. Publications 50. Tampere 1988. 106 p.

2. Kluft, W. Techniken zur Werkzeugüberwachung auf der Basis von Kraft- und Verformugsmessung. Sonderdruck aus der Vortagsreihe des VDI-Seminars "Überwachung und Diagnose von Maschinen und Prozessen " von 3 -4-Juni 1985 in Aachen, Germany. 14 p.

3. Jantunen, E. & Jokinen, H. Automated on-line diagnosis of cutting tool condition. 5th International Conference of Flexible Automation & Intelligent Manufacturing, FAIM 95, June 28-30, 1995, Stuttgart, Germany

4. Randall, R.B. Application of B&K equipment to frequency analysis. In Brüel & Kjær. Nærum, Denmark. 239 p.

5. Jantunen, E. & Poikonen, A. Dynamics in monitoring gear faults. Proceedings of the 47th meeting of the mechanical failures prevention group. Virginia Beach, Virginia, USA, April 13-15 1993. p. 279-288.