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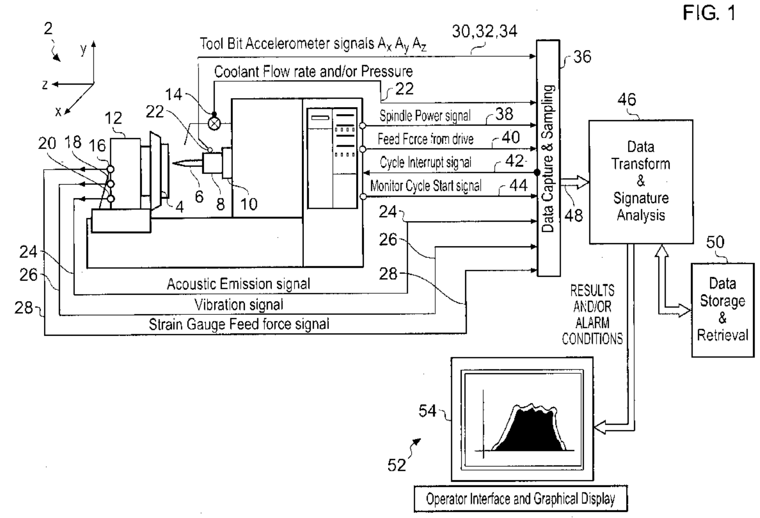
FIG. 1



(57) Abstract: The invention concerns a manufacturing process monitor, in particular a machining process, and a method of multi-parameter data acquisition and analysis for process diagnostics. Multiple sensors (14, 16, 18, 20, 22) are attached to a machine tool (2) to monitor a plurality of machining parameters including machine power consumption, acoustic emissions, vibration, power and force. During each operation the sensor outputs (24, 26, 28, 30, 32, 34, 38, 40) are repeatedly sampled (36) and processed (46) to provide a signature (54) characteristic of the operation. The data is analysed to determine the limits of a normal machining operation, including the condition and status of the tools (6) and equipment (2). By storing the signatures (50) for a large number of operations of known "normal" and "abnormal" outcomes a data population is created with which new signatures can be compared and a diagnostic indication (54) produced. Warnings of abnormalities and abnormal events, such as tool damage, may be produced automatically and in real-time.

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MACHINING PROCESS MONITOR

The invention relates to a method of process monitoring a component manufacturing operation and process monitor apparatus.

In particular the invention concerns on-line detection and recognition of manufacturing process malfunctions or abnormal operations and events, and their resulting component anomalies, using an advanced signal-processing algorithm.

Data collection for the purpose of process monitoring in a number of industries has been performed for many years. It has been applied to monitor the condition of the product, the process, and the machines performing the process and tools that may be used by the machines. Typically a plurality of sensors have been attached or positioned to collect data about a number of variables. The sensor outputs are linked to a data collection and analysis processor in which they are compared with stored values and the process etc. is judged to be operating within or outside expected parameters. Data representing a "good" process are first collected, for example in a cutting process using new tools, so that the system is taught or learns what is a good process, or an operator can judge an appropriate limit level. Using this data as a reference, the system or operator calculates boundary conditions based on the learned data. In normal operation the system continually monitors the sensor outputs and, if a boundary limit is breached, will issue an audible warning and/or issue a signal to interrupt or halt the process. In this way gross malfunctions such as extreme tool wear or failure (even impending failure) can be captured preventing breakage and consequential component damage. However, such systems only issue an alarm or halt the process and do not diagnose the cause of the fault.

Power monitoring is another widely used monitoring method in which machine tool power is monitored on simple upper and lower gated limits. The method tends to lack sensitivity, however. A machine capable of handling a physically large component almost invariably is supplied with a large, high power spindle. In order to avoid resetting a component between individual operations, and therefore losing its zero datum each time, all operations are performed on a single machine. Thus, the same machine tool will be utilised for turning, cutting, and drilling. For example all of the operations required to produce a disc of 1 meter diameter, having up to 100 holes each of 6 millimetre diameter will be performed using a single machine. The power needed to drill a 6 millimetre hole is a small even insignificant fraction of the power required to turn the outer circumference of the disc. Thus, a power monitoring method is not adequately sensitive to the small changes caused by a process malfunction during a drilling operation.

Machining process monitors are known in the art. For example United States Patent 5,822,212 describes a machining load monitoring system in which machining load in a trial cutting process is sampled and measurements stored. Corresponding measurements made during an actual cutting process are then compared with the stored data and an alarm raised when the difference between the compared data values reaches or exceeds a predetermined level. In order to overcome timing differences between the stored reference and actual measured data, the timing of the sampled data values are related to machine control instructions issued by the machine controller. However, problems still arise with systems of this kind due to the nature of limit setting, not too high to miss serious defects and not too low to generate excessive false alarms, but nevertheless they are generally unable to predict incipient failure or other subtle “abnormalities”.

United States Patent 5,070,655 concerns a machine tool monitor having sensors arranged to provide power and vibration signals to a controller, which processes the signals in order to detect a change in the machine processing parameters. The monitor apparatus may issue audible and visual alarms to alert an operator, and may automatically halt the machining operation. The monitor further indicates whether the condition of the tool and its associated machining operation warrants scrutiny or service. An example is described in which a grinding machine, provided with power and vibration sensors, has a controller adjusted to signal conditions associated with grinding wheel sharpness, loss of coolant, and excessive vibrations. When the level of a measured parameter exceeds a predetermined limit an alarm is triggered.

In general, existing systems of this kind remain too coarse in their sensitivity to anticipate an incipient failure and, moreover, they are unable to distinguish between the possible failure causes. Process monitoring systems of this kind do not provide sufficiently reliable detection of manufacturing process malfunctions, and it is found that the system functionality is restricted to detecting tool presence, broken tool detection, tool wear and impending tool failure. In the main, existing process monitors are seen as unreliable, difficult to configure and maintain and troubled by false alarms. False alarms occur when the system issues an alarm in response to a monitored signal exceeding a limit other than for a process malfunction. In practice an operator often deals with this phenomenon by switching off the process monitor to prevent further interruptions due to false alarms.

A need for the invention arises in aeroengine manufacture for monitoring of critical rotating component manufacturing processes. At one level, detection of impending cutting tool failure will prevent tool breakage and consequential damage. The costs associated with a broken tool on critical components arise from laboratory investigations and testing to determine effects on the component, the cost of tooling replacement and repair, the cost of re-work and possibility of a scrapped component (which can be particularly costly). At another level undetected surface damage can lead to in-service failure. Where the component in question is built into a safety critical assembly the consequences of failure may include possible loss of life.

The present invention seeks to provide a solution to the problems inherent in known process monitoring methods by simultaneously monitoring several different parameters and combining the individual results in such a way as to eliminate false alarms and provide a more versatile and sensitive record of the component manufacture.

A further objective of the invention is to provide a monitoring process that not only detects gross process malfunctions, but also is able to distinguish between gross process malfunctions and normal tool wear. In addition it is intended that the method shall be able to detect the production of surface anomalies caused by process malfunctions undetected by known process monitoring systems. Moreover, it is intended to provide an indication of the likely cause of a surface anomaly and its likely effect on component surface integrity.

According to one aspect of the present invention there is provided a method of process monitoring a component manufacturing operation comprises: attaching a plurality of sensors to a component manufacturing machine to measure a plurality of "n" machining parameters, sampling the sensor outputs during a manufacturing operation cycle, processing the sampled sensor outputs to produce a characteristic signature for each process cycle, storing a multiplicity of characteristic signatures, comparing each newly produced characteristic signature with stored characteristic signatures, and providing an output in accordance with the result of said comparison to indicate whether or not the process is a "normal" or "abnormal" process.

Preferably the plurality of sensors are arranged to measure a plurality of machining parameters including machine power consumption, tool bit accelerations, acoustic emissions, vibration and tool feed force, and the tool bit acceleration sensors are arranged preferably to measure tool bit accelerations in three mutually perpendicular planes.

According to another aspect of the invention the output from each of the plurality of sensors is repeatedly sampled during a process cycle to provide a stream of time domain data.

According to further aspects of the invention time domain data are transformed into the frequency domain using a Fast Fourier Transform. Preferably in each process cycle time domain data from each of the sensors are captured in at least one data window and the data in each data window are transformed into the frequency domain using a Fast Fourier Transform. During each process cycle time domain data from each of the "n" sensors may be captured in a plurality of at least partially overlapping data windows and the data in each data window transformed into the frequency domain using a Fast Fourier Transform.

In the preferred form of the invention "n" data streams each associated with a different sensor are combined in an "n"-dimensional space to produce at least one characteristic signature or a vector for an individual manufacturing operation cycle or part thereof. Preferably the characteristic signatures of a multiplicity of preceding manufacturing operation cycles are stored and a characteristic signature corresponding to a new manufacturing operation cycle is compared with the stored signatures to determine if the new operation cycle is "normal" or "abnormal".

The invention and how it may be carried into practice will now be described in greater detail with reference by way of example to the accompanying drawings, in which:

Figure 1 shows a schematic diagram of a shop floor machine tool and process monitor system incorporating the invention;

Figures 2a, 2b, 2c, and 2d show graphical representations of time-series data in five sensor channels captured during a "normal" drilling operation;

Figure 3 shows a graphical representation of spindle power variation over time during a "normal" drilling operation;

Figure 4 shows a functional diagram of the data transform and signature analysis method steps of the invention;

Figure 5 shows a typical characteristic signature of a variable "y" (e.g. Acoustic Emission) constructed with respect to a system operating point (e.g. Spindle power); and

Figure 6 shows a 2-dimensional visualization of a multi-dimensional signature illustrating clustering of "normal" and "abnormal" operations.

Illustrated in Figure 1 is a numerically controlled machine tool generally indicated at 2, for the purposes of this description and solely by way of example, the machine is shown with a drill bit ready to perform a drilling operation. A workpiece upon which a machining operation of a drilling operation is to be performed, in this example, is shown by reference numeral 4. A tool 6, i.e. a drill, is mounted in a tool holder 8 carried by the machine spindle 10; the workpiece 4 is mounted in a suitable machining fixture indicated generally at 12, this may include a rotatable table to which the workpiece is fixed.

The machine tool 2 is fitted with a number of monitoring devices or sensors 14, 16, 18, 20 which respectively monitor coolant flow rate, spindle or workpiece feed force, workpiece vibration, and workpiece acoustic emissions. An accelerometer 22 is mounted on the tool bit holder 8 or machine spindle 10 to measure accelerations of the tool bit in three mutually orthogonal planes designated x, y and z, see Fig 1. These are planes fixed with respect to the bed of the machine tool 2. This list of monitored parameters is not exclusive and further parameters may be measured depending upon requirements, but we have found so far that those listed as sufficient for present purposes. The output signals: coolant flow rate signal 22; acoustic emission signal 24; vibration signal 26; feed force signal 28; and accelerometer signals 30, 32, 34 are connected to data capture and sampling units indicated at 36. In addition further signals representing spindle power 38; spindle feed force 40; cycle interrupt 42 and monitor cycle start 44 are supplied directly from the machine tool control system to the data capture unit 36. In practice if a feed force signal 40 is provided from the spindle drive mechanism of the machine tool 2, this is often provided as a feedback signal in a numerically controlled machine, then it is not necessary to also provide a strain gauge sensor 16 in order to measure the same force at the workpiece and provide signal 28. Thus, normally only one of signals 28 and 40 would be present, but not both.

Data captured and sampled by unit 36 is passed to a data transform and signature analysis unit 46 for processing and evaluation. Unit 46 comprises a digital computer programmed to perform the complex calculations necessary to transform the input data signals to produce the characteristic signature representing each process cycle, and to compare each new signature with stored signatures for evaluation purposes and to determine if a process is "normal" or "abnormal". The computer unit 46 is connected to a data storage unit 50 for the purpose of storing new data and for retrieving previously stored data. The computer unit 46 is also connected to an operator interface and graphical display unit generally indicated at 52. Typically this is also a computer having a display screen 54, upon which information is presented for viewing by an operator, and a keyboard by means of which the operator may enter commands etc.

The outputs from the various sensors are sampled at a predetermined sampling rate. The raw data is therefore acquired in the time domain and is not in the most suitable form for constructing a characteristic signature and determining whether an individual process cycle is "normal" or "abnormal". For example in a drilling process the tool 6 carried in the toll bit holder 8 is rotated and moved transversely with respect to the workpiece 4. The sensor outputs therefore exhibit peaks in vibration amplitude at the fundamental rotational frequency of the machine spindle when observed in the frequency domain. Although the vibration amplitudes can be used to characterise the manufacturing process, as the data are acquired in the time domain, the characteristics are not easy to identify in their initial format. In accordance with the method of the present invention the acquired data are transformed into the frequency domain.

According to the present method the outputs from the plurality of sensors are repeatedly sampled during a process cycle to provide a stream of time domain data, see 48 in Figure 1. The data are transformed into the frequency domain using a Fast Fourier transform (FFT). Each time domain signal was divided in each process cycle into a number of windows, each of a relatively large number of points, and the FFT was performed on each window. In the particular example being described the data were divided into windows of 4096 points, and a 4096-point FFT was performed on each data window. At a sampling frequency of 20 KHz this corresponded to approximately 5 FFTs per second of data. It was found by experience that this provided sufficient resolution for identifying frequency-based events indicative of system abnormalities.

Referring now to the drawings contained in Figure 2, there are shown at Fig 2a, Fig 2b and Fig 2c the three time-series spindle accelerometer signals A_x, A_y and A_z on channels 30, 32, 34 respectively; and Fig 2d shows the acoustic emission signal on channel 26. Fig 3 shows the spindle power signal 38. In all cases the horizontal axis represents time, note that Figs 2-d inclusive have a common scale but Fig 3 has a slightly different time scale so although events in the first four illustrations are vertically aligned, the same event is slightly displaced in Fig 3. It is apparent from a visual inspection of Fig 3 that the drilling process cycle can be conveniently divided into three stages: stage 1 – initial drilling into the disc; stage 2 – a peak power period where the drill-bit breaches the rear plane of the disc; and stage 3 – final withdrawal of the drill-bit from the disc. Drill power-on and power-off events are clearly seen at the start an end of a process cycle as transient spikes. The drill unit is then moved towards the static disc at a constant feed rate between t = 12 seconds and t = 27 seconds corresponding to approximately constant values of spindle power Fig 3, acoustic emission Fig 2d, and low amplitude accelerations in the x-, y- and z-planes, Figs 2a, 2b and 2c. At t = 27 seconds the drill makes contact with the static disc and begins to drill into the metal. Commencement of the initial drilling stage 1 corresponds to a step-change in spindle power to a higher level and stays approximately constant until t = 38 seconds. During this time acoustic emission increases to a largely constant, non-zero value. The value of A_z (Fig 2b) also remains approximately zero, but A_x and A_y increase throughout this drilling operation. At t = 38 seconds the tip of the drill-bit passes through the rear face of the disc; spindle power increases until t = 44 seconds, vibration and acoustic emission reaches a correspondingly high value while A_x and A_y hit a transient peak and then decrease in amplitude. At t = 44 seconds the drill-bit has fully breached the rear of the disc and the direction of the drill unit is reversed, such that the drill is retracted form the disc. Until t = 46 seconds the values of spindle power and vibration amplitude decrease rapidly. The cycle ends at t = 51 seconds witnessed by spikes in the traces of Figs 2a, 2b, 2d and 3.

Fig 4 shows a functional diagram illustrating the data capture, transformation and analysis procedure performed by unit 46 of Fig 1. The raw sensor data at 48 is readied for analysis by a pre-processing or signal conditioning step 60 in order to remove background noise, unrelated artefacts such as transient power spikes, power supply components and spectral components below a minimum power threshold, as is well known in the art. The time-series data 61 is then loaded into data windows 62a, 62b, 62c [three such windows are shown merely by way of example only]. As each window is filled a Fast Fourier transform is performed on the contents to transform the data from time domain signals into the frequency domain signals 64a, 64b, 64c. At the end of a process cycle a number of FFTs will have been performed, thus generating a set of "spectral features" unique to the process cycle. If there are "n" sensor channels the FFT transforms performed on the full suite of data available will yield "n" feature sets for each process cycle. A set of features is derived from each of the "n" input sensors in feature extraction step 66. In general, "m" features are obtained from each of the "n" sensors, however the number of features in each set may be variable. An example of a feature is a significant frequency. The processed data are normalised in step 68 to ensure comparison between features is performed without dependence on absolute values, such that the units of measurement for each feature are not significant.

Using the normalised features a characteristic signature is constructed in block 70, labelled "analysis" in the diagram. Each new characteristic signature is compared with a set of stored characteristic signatures 72 by a decision block 74, which decides whether or not a signature is "normal" or "abnormal". A "yes" decision at 76 indicates a successful operation and, as indicated by process block 78, either the machining operation is allowed to continue towards completion or it is successfully completed. However, if the output form decision block 74 is a "no" the signature is analysed more precisely, as indicated by process block 80, to determine whether the process is "abnormal" or a "high limit" has been exceeded and the operation must be stopped immediately, or whether it merely warrants a warning but may be allowed to continue towards completion.

With the use of multiple, time separated data windows during each process cycle a plurality of points are available for each cycle spaced apart through the cycle. It therefore becomes possible to construct a characteristic signature for each and every process cycle. Thus, the signature of a variable "y" throughout a process cycle can be constructed with respect to the operating point of the system as illustrated in Figure 5 by the solid black line. It will be self-evident that no two such process cycles can yield identical characteristic signatures, but excluding failures, all will to a greater extent be similar. Nevertheless a spread will be evident in both the original data and in the spectral features that characterise individual cycles; this is represented in Figure 5` by the dashed curves above and below the solid curve. The position of these upper and lower limits is selected by reference to the distribution of the data population. For example the limits of normality may be set to capture a chosen percentage, say 99%, of the results. A result, or signature, falling inside of these limits is deemed to be "normal" and a signature outside of the limits is deemed to be "abnormal". A probabilistic approach such as this has an arbitrary element, at least initially, but by learning through experience the limits can be adjusted in order to exclude or include components that visual inspection and physical analysis show to be wrongly categorised. In this way a practically useful, tool-specific model of "normality" may be constructed.

The use of numerous channels makes visual interpretation of the raw data extremely difficult. Single channel inspection, as in most of the above-mentioned prior art examples is highly susceptible to erroneous false alarms. On the other hand, multiple data channels make holistic exploration of the data too difficult, as visualisations typically only cope with 2- or 3-dimensional data. Higher dimensional data, that is data that requires more than two or three dimensions to represent, can be difficult to interpret. One approach to simplification, especially with a view to visualisation of the data, is to use a mapping procedure, such as Sammon's mappijng, to project the signatures into 2 dimensions. The mapping process to produce this result may be carried out using a neural network.

The present invention seeks, therefore, to combine the multi-dimensional data features in such a way that the whole can more easily be visualised and interpreted. In Figure 4 this step is performed in the block 70, the function performed in the block 70 is to combine the data features in "m"-dimensional space into a single characteristic vector or point unique to the particular process cycle. The data may be manipulated to produce either a single point representing a complete cycle or a series of points representing different time periods of a cycle. In the system illustrated in Figure 1 five features were used to construct signatures for each process cycle. The data channels represented in Figures 2a-2d and Figure 3 produce time related measurements throughout a process cycle. After performing a Fast Fourier transform on the data there are five concurrent feature samples A_x, A_y, A_z, AE and SP. The signature variables chosen consisted of AE amplitude vs. SP; A_x broadband power vs. SP; A_z broadband power vs. SP; A_x average significant frequency μ_f vs. SP; A_z average significant frequency μ_f vs. SP. These are then combined to produce a five dimensional vector. Visualisation is performed on the "m" features extracted from each of the "n" original channels of sensor data and may be displayed on screen 54 for operator inspection. An example of one such visualisation is shown in Figure 5 which illustrates a visualisation in which acoustic emission is plotted against spindle power and includes two points one deemed as "normal" and the other as "abnormal".

Figure 6 shows a two-dimensional mapping obtained using a large number of results produced from the A_x accelerometer shown at Fig 2a, which is an example of a visualisation from original "m"-dimensional space into 2-dimensions. Clearly visible from this 2-dimensional map is the clustering of a great many of the results as well as the overall spread in the distribution of all results. Each signature point is represented in the drawing by a cross, and a degree of clustering is evident in this visualisation of a large number of process signatures. A main cluster of signature points deemed to be "normal" is labelled in the drawing and the limit of within which a signature, and the process with which it is associated, is accepted as "normal" is indicated by a dashed line. Points outside the enclosed space are deemed to be "abnormal" results. In these tests the tool was used repeatedly beyond the point where it would normally have been replaced, in order to generate test data from a worn tool. The trend attributable to tool wear is indicated by an arrow in the drawing. A signature change caused by an anomaly or other significant event will produce a data point distinctly separate from the "normal" cluster. These points will usually exhibit their own clustering. By way of example two such "abnormal" clusters are indicated in the drawing. Events such as, for example, "tool chipping" and "loss of coolant" could be expected to produce distinctively separate and identifiable clusters of their own.

The method of the invention not only detects gross process malfunctions but also is able to distinguish between gross process malfunctions and normal tool wear, and is able to recognise events, individually or in combination, indicative of the production of component surface anomalies. This new process is able not only to detect events that may have created a surface defect, but also to inform of the likely cause and what likely effect on surface integrity may be expected. Malfunctions and anomalies are recognised at the data evaluation stage in the combined and fused data as departures from normality. In a normal drilling process, for instance, the analysed data for successive drilled holes will be dimensionally similar and clustered closely together. Increasing but acceptable tool wear will cause the data to drift away from the initial, normal position until an acceptable limit is reached. In the event a limit is breached action to halt the process is taken.

In operation of the system a pre-determined number of holes is machined using new tools, and the resulting sensor output signals are collected and evaluated and the results stored as a reference data set. In this way the "control" or "normal" data signatures are established. During subsequent process monitor cycles the sensors are continuously monitored and the sensor output signals are evaluated and compared with the reference data or control group. On the basis of rules determined *a priori*, control limits are set about the reference data group to accommodate normal tool wear. Should these limits be exceeded the system will issue a warning to the operator, for example to change tools. Deviation from the reference group is deemed as a departure from a normal process and the system is pre-programmed to issue an appropriate warning, and if necessary to halt the machining operation. Departures from normality are characteristic of a process malfunction or production of a surface anomaly. Based on learned experience the system is also arranged to produce an indication of the most likely cause of the event. This speeds up decision making on component sentencing and/or machine maintenance in the event that a machine fault is suspected. Following remedial action normal processing is resumed.

The method of the present invention is applicable to a wide range of machine tools and operations. All conventional machining processes can be monitored by the system described above including milling, broaching, turning, grinding (all types), drilling, reaming, hobbing, shaping, burnishing, honing etc. With the substitution or inclusion of different sensors for example thermal, pressure, current, other and less conventional machining processes may be monitored such as EDM (electro discharge machining), ECM (electro chemical machining), wire cutting, laser cutting, laser welding, abrasive water jet machining, chemical milling etc. Furthermore other processes may be monitored, such as casting, forging, stamping/pressing, rolling, hot- and cold- cropping, injection moulding, die casting, friction and inertia welding both rotary and linear kinds, super plastic forming etc.

CLAIMS

1 A method of process monitoring a component manufacturing operation comprises: attaching a plurality of sensors to a component manufacturing machine to measure a plurality of "n" machining parameters, sampling the sensor outputs during a manufacturing operation cycle, processing the sampled sensor outputs to produce a characteristic signature for each process cycle, storing a multiplicity of characteristic signatures, comparing each newly produced characteristic signature with stored characteristic signatures, and providing an output in accordance with the result of said comparison to indicate whether or not the process is a "normal" or "abnormal" process.

2 A method as claimed in claim 1 wherein the plurality of sensors are arranged to measure a plurality of "n" machining parameters including machine power consumption, tool bit accelerations, acoustic emissions, vibration and tool feed force.

3 A method as claimed in claim 2 wherein tool bit acceleration sensors are arranged to measure tool bit accelerations in three mutually perpendicular planes.

4 A method as claimed in any preceding claim wherein the output from each of the plurality of "n" sensors is repeatedly sampled during a process cycle to provide a stream of time domain data.

5 A method as claimed in claim 4 wherein the time domain data are transformed into the frequency domain using a Fast Fourier Transform.

6 A method as claimed in claim 5 wherein in each process cycle time domain data from each of the "n" sensors are captured in at least one data window and the data in each data window are transformed into the frequency domain using a Fast Fourier Transform.

7 A method as claimed in claim 6 wherein during each process cycle time domain data from each of the "n" sensors are captured in a plurality of at least partially overlapping data windows and the data in each data window are transformed into the frequency domain using a Fast Fourier Transform.

8 A method as claimed in any one of claims 4 to 7 wherein "n" data streams relating to each sensor are combined in an "n"-dimensional space to produce at least one characteristic signature or a vector point for an individual manufacturing operation cycle or part thereof.

9 A method as claimed in claim 8 wherein the characteristic signatures of a multiplicity of preceding manufacturing operation cycles are stored and a characteristic signature corresponding to a new manufacturing operation cycle is compared with the stored signatures to determine if the new operation cycle is "normal" or "abnormal".

10 A method as claimed in claim 9 wherein an operation cycle is deemed "normal" if the characteristic signature point falls within limits determined with reference to the stored population of characteristic signatures.

11 A method as claimed in claim 10 wherein the said limits are set to capture a proportion, for example 99%, of the stored population, and a new signature falling outside of the said limits is deemed to be "abnormal".

12 A method as claimed in any one of claims 9 to 11 wherein the population of stored signatures is further categorized according to identified faults and failures.

13 A method as claimed in claim 12 wherein an indication of an "abnormal" operation includes an indication of a fault or failure.

14 A method as claimed in claim 13 wherein an indication of an "abnormal" operation is provided in real-time.

15 A method as claimed in claim 12 or 13 wherein an indication of an "abnormal" operation includes an immediate halt of the manufacturing operation.

16 A method as claimed in any preceding claim including producing a visualisation of the process characteristic signature.

17 A method as claimed in claim 16 wherein the visualisation of the process characteristic signature comprises a two-dimensional visualisation.

18 Process monitor apparatus for monitoring the performance of a manufacturing machine is adapted and arranged to operate in accordance with a method as claimed in any one of claims 1 to 17.

19 Process monitor apparatus as claimed in claim 18 comprising a plurality of machine parameter sensors, means for sampling the sensor outputs, means for producing a characteristic signature for each process cycle, means for storing a multiplicity of characteristic signatures, and means for comparing a new characteristic signature with the stored characteristic signatures, and means to provide an output in accordance with the result of the comparison.

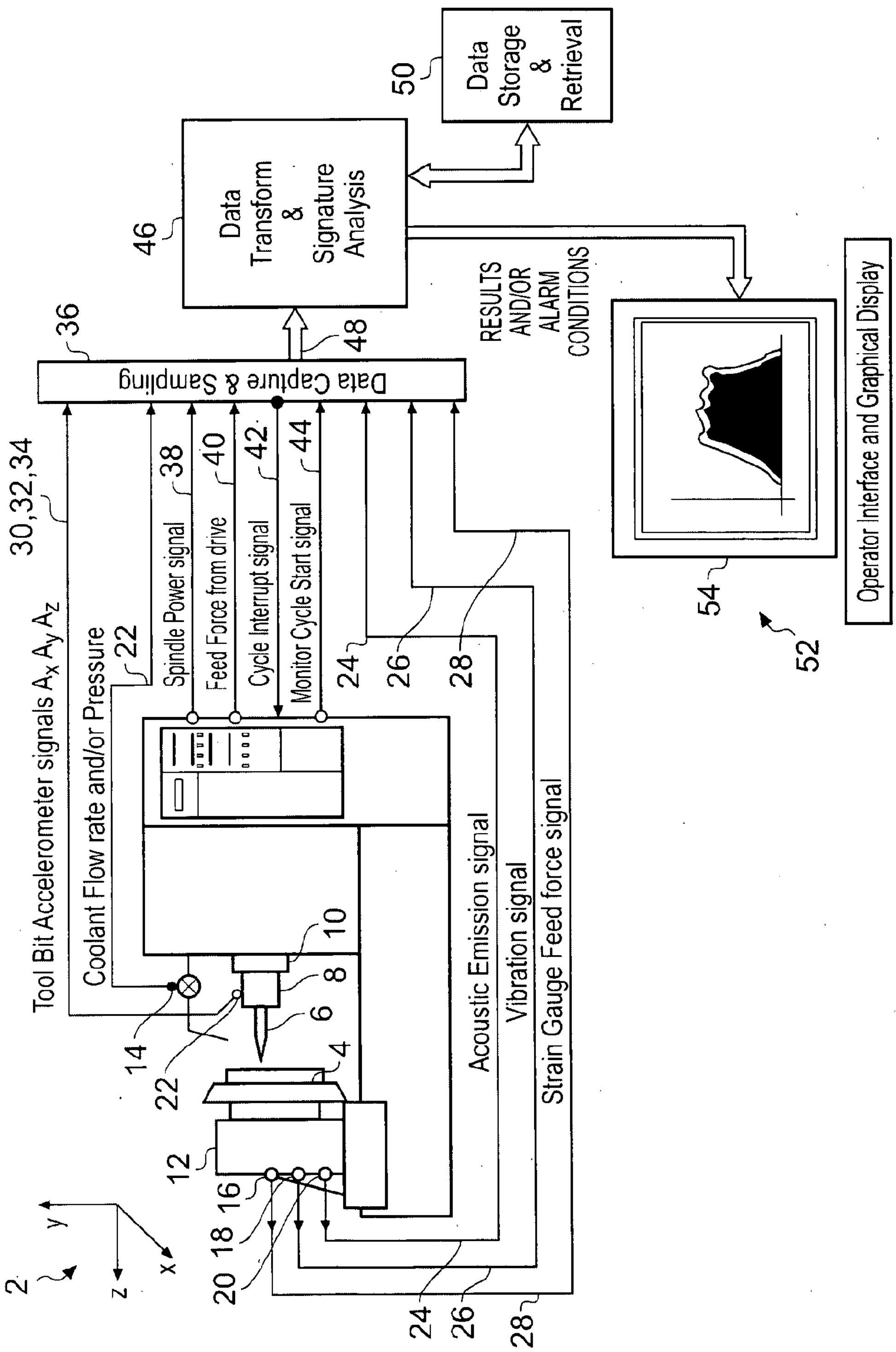
20 Process monitor apparatus as claimed in claim 19 further comprising means to produce a visualisation of the process signature.

21 Process monitor apparatus as claimed in any of claims 18 to 20 further comprising means to produce an output indicative of an "abnormal" operation.

22 Process monitor apparatus as claimed in claim 21 further comprising means adapted to halt an operation in the event of production of an indication of a selected "abnormal" operation.

23 A method process monitoring a component manufacturing operation substantially as hereinbefore described with reference to the accompanying drawings.

24 Process monitor apparatus for monitoring the performance of a component manufacturing machine substantially as hereinbefore described with reference to the accompanying drawings.


Tool Bit Accelerometer signals A_x A_y A_z
30,32,34
Coolant Flow rate and/or Pressure
22
Spindle Power signal
38
Feed Force from drive
40
Cycle Interrupt signal
42
Monitor Cycle Start signal
44
24
26
28
Data Capture & Sampling
36
48
Data Transform & Signature Analysis
46
Data Storage & Retrieval
50
RESULTS AND/OR ALARM CONDITIONS
Operator Interface and Graphical Display
54
52
Acoustic Emission signal
Vibration signal
Strain Gauge Feed force signal
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4
14
22
12
16
18
20
24
26
28

FIG. 1

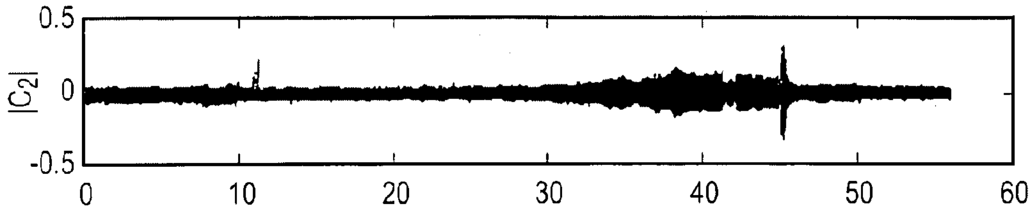

FIG. 2a A_x

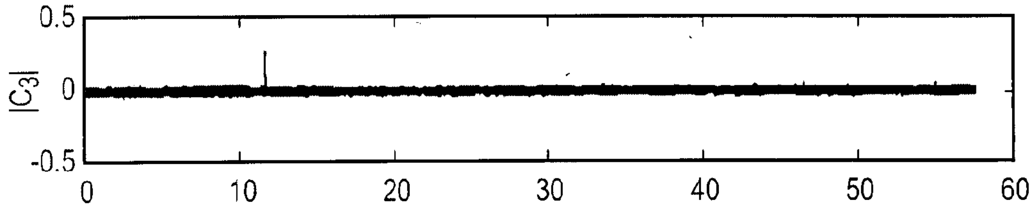

FIG. 2c A_z

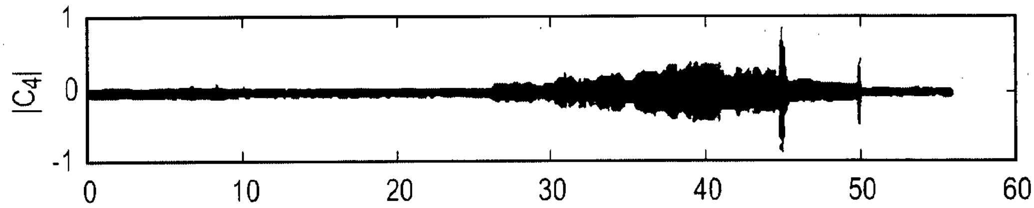

FIG. 2b A_y

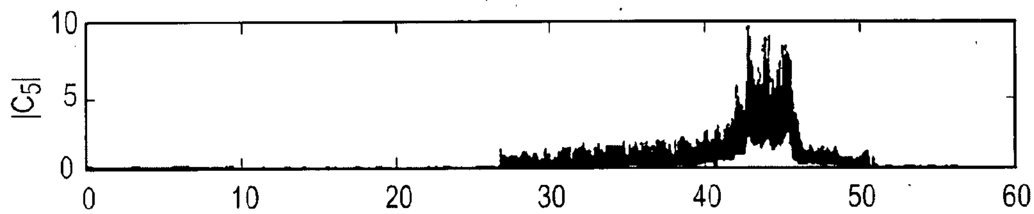

FIG. 2d AE

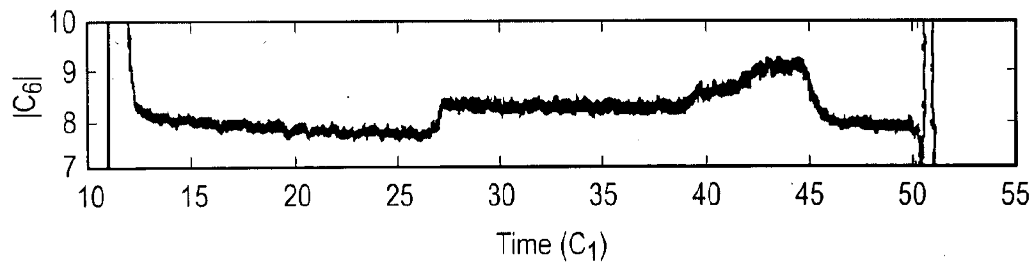

FIG. 3 Spindle Power

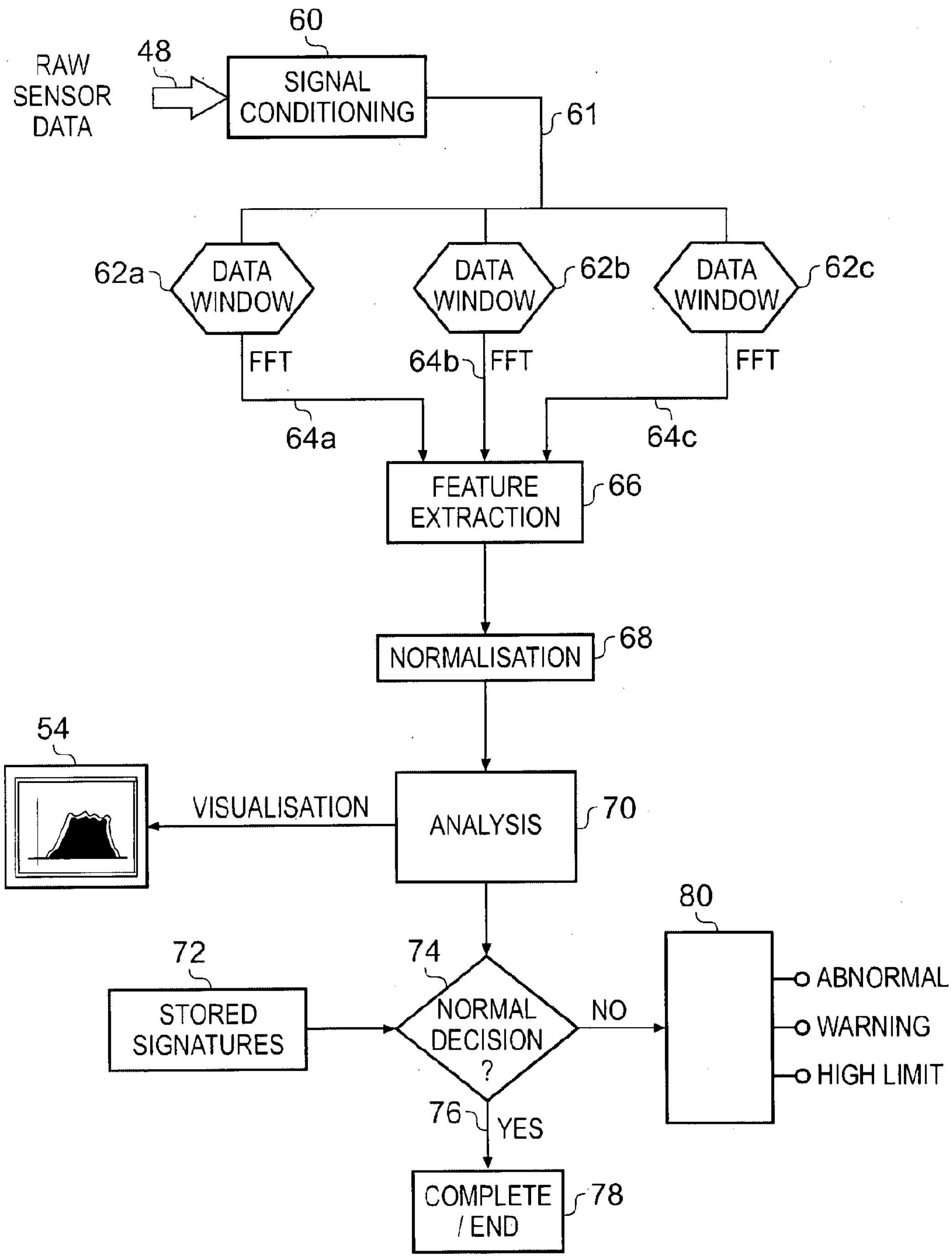
60
48
RAW SENSOR DATA
SIGNAL CONDITIONING
61
62a
DATA WINDOW
62b
DATA WINDOW
62c
DATA WINDOW
FFT
64b
FFT
FFT
64a
64c
FEATURE EXTRACTION
66
NORMALISATION
68
54
VISUALISATION
ANALYSIS
70
80
72
74
STORED SIGNATURES
NORMAL DECISION ?
NO
ABNORMAL
WARNING
HIGH LIMIT
76
YES
COMPLETE / END
78

FIG. 4

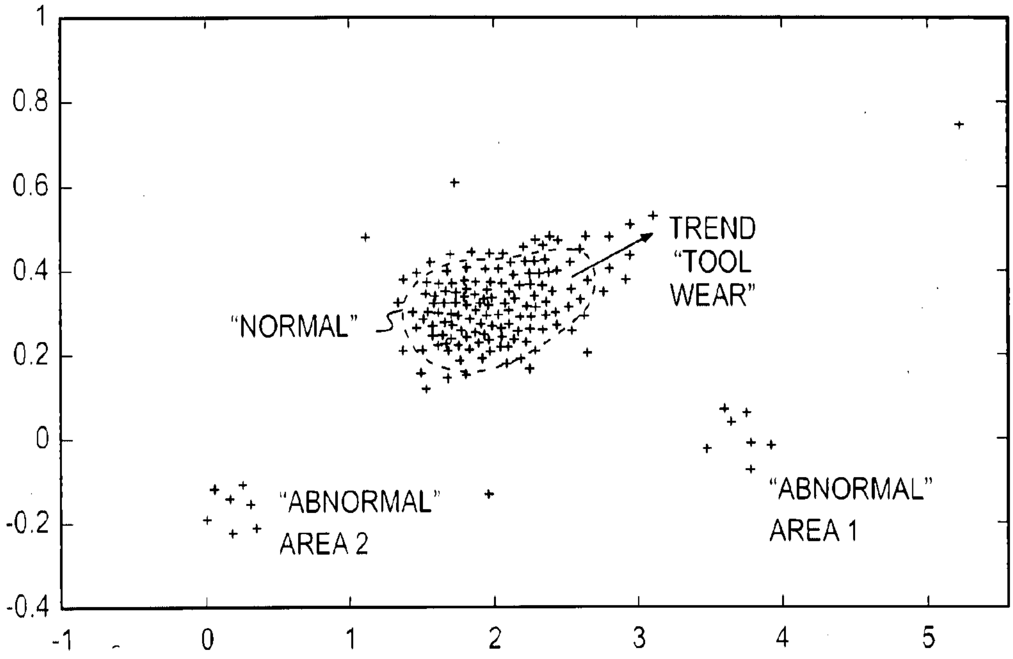
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-1
0
1
2
3
4
5
TREND
"TOOL
WEAR"
"NORMAL"
"ABNORMAL"
AREA 2
"ABNORMAL"
AREA 1

FIG. 6

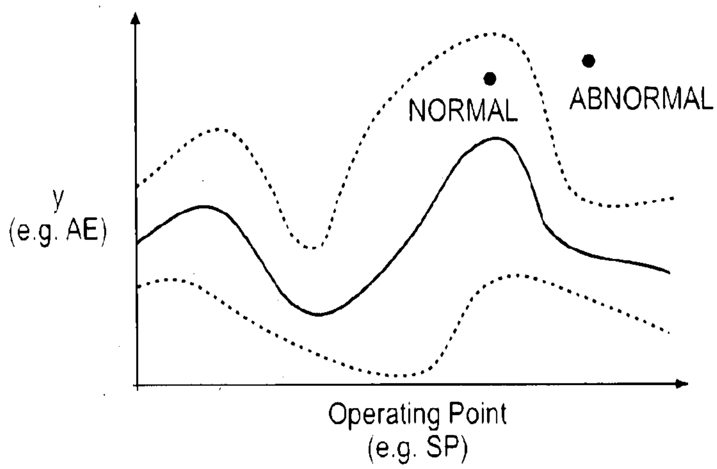
NORMAL
ABNORMAL
y
(e.g. AE)
Operating Point
(e.g. SP)

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2008/001700

A. CLASSIFICATION OF SUBJECT MATTER
INV. G05B19/4065

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 6 041 287 A (DISTER CARL J [US] ET AL) 21 March 2000 (2000-03-21) column 2, line 56 - column 4, line 19 column 8, line 24 - column 11, line 27 column 15, line 19 - column 17, line 31 column 20, line 4 - column 21, line 65 claims 1-4; figures 19-22	1-10, 12-22 11
Y A	WO 00/31510 A (FEDERAL MOGUL CORP [US]) 2 June 2000 (2000-06-02) page 3, line 5 - page 5, line 8 page 7, line 10 - page 12, line 2 page 16, line 4 - page 19, line 21 claims 1-6; figures 7-27	11 1,2,4-6, 9-22

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 July 2008	22/07/2008

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Orobitg Oriola, R

2

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 586 041 A (MANGRULKAR SURESH M [US]) 17 December 1996 (1996-12-17)	1-4, 8-11, 16-22
A	column 2, line 2 - column 3, line 5 column 4, line 16 - column 10, line 32 column 12, line 21 - column 13, line 66 figures 4-6,10,12,13	14,15
X	WO 03/019627 A (CABOT MICROELECTRONICS CORP [US]) 6 March 2003 (2003-03-06)	1-10, 12-22
Y	paragraph [0010] paragraph [0015] - paragraph [0027] paragraph [0031] - paragraph [0042] figures 1-4	11
X	US 2006/184264 A1 (WILLIS JAMES E [US] ET AL) 17 August 2006 (2006-08-17) paragraph [0008] - paragraph [0010] paragraph [0020] - paragraph [0092] paragraph [0130] - paragraph [0236]	1-4,8-22
X	WO 02/095514 A (CURVACEOUS SOFTWARE LTD [GB]; BROOKS ROBIN WILLIAM [GB]; WILSON JOHN G) 28 November 2002 (2002-11-28)	1-4, 8-11, 16-22
A	page 1, line 1 - page 2, line 33 page 3, line 29 - page 12, line 20 figures 3-9	14,15

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB2008/001700

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [ ] Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. [X] Claims Nos.: 23,24
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. [ ] Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. [ ] As all required additional search fees were timely paid by the applicant, this international search report covers allsearchable claims.

2. [ ] As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this international search reportcovers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

[ ] The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

[ ] No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.2

Claims Nos.: 23,24

The claims 23 and 24 rely merely on references to the description and drawings and do not consequently meet the requirements of Rule 6.2 PCT. A meaningful search was not possible for these claims, since it is completely unclear which features of the description and/or the drawings have to be considered as part of these claims.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.2), should the problems which led to the Article 17(2)PCT declaration be overcome.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2008/001700

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
US 6041287	A	21-03-2000	NONE			
WO 0031510	A	02-06-2000	EP	1133687	A1	19-09-2001
			JP	2002530768	T	17-09-2002
US 5586041	A	17-12-1996	NONE			
WO 03019627	A	06-03-2003	AU	2002327481	A1	10-03-2003
			CN	1606720	A	13-04-2005
			EP	1421453	A2	26-05-2004
			JP	2005501410	T	13-01-2005
			TW	556282	B	01-10-2003
			US	6431953	B1	13-08-2002
US 2006184264	A1	17-08-2006	KR	20070117579	A	12-12-2007
			WO	2006088545	A2	24-08-2006
WO 02095514	A	28-11-2002	AT	396442	T	15-06-2008
			CA	2446688	A1	28-11-2002
			EP	1402324	A2	31-03-2004
			GB	2378527	A	12-02-2003
			JP	2004527057	T	02-09-2004
			US	2004113912	A1	17-06-2004