Systems Integration in Maintenance Engineering

Andrew Starr, Andrew Ball

Maintenance Engineering Research Group

Manchester School of Engineering

University of Manchester

Abstract

Integration in maintenance engineering systems provides a potential solution to some complex and conflicting problems. Decision making is often achieved with uncertainty and unknowns, while measuring against conflicting performance criteria. Maintenance decisions are made in the context of business priorities.

Integration must consider the bi-directional flow of data and information into the decision making and planning process at all levels. This reaches from business systems right down to sensor level. Integration automates the organisation and operation of systems, data collection and actuation, information storage and decision making. Critically, integrated systems display the evidence of thorough top-down system design, which incorporates the elements above, and closes the loop from the minutiae of data collection to strategic decision making.

This paper introduces the systems associated with maintenance and draws comparisons with adjacent disciplines such as control. A globalised model is proposed, and methods for selecting and adapting technologies for the model are discussed. Examples of industrial implementation are shown at several levels within the model.

Key words: Maintenance Engineering, Integration, Condition Monitoring, Control, Communications

1. Introduction

Integration is a holistic approach: it sets objectives for a system as a whole, hence specifications. The systems approach determines inputs and outputs, and in this context maintenance engineering aims to optimise outputs such as reliability, availability, and cost, using inputs such as expertise, information, and resources, both human and physical.

In the traditional maintenance department, the systems in place organise resources against scheduled and unscheduled tasks in many different ways, all of which are effective in their own way:

- simple communications, by word of mouth or on paper;
- time based planning on cards or wall charts;
- computerised inventory, spares and job planning.

These methods have limitations in speed, automation and optimisation. Integration can only be achieved in the former cases by detailed manual transfer of data from one system to another, whether inside the maintenance department, e.g. decisions emanating from condition monitoring, or outside, e.g. transfer of costing information to a financial system. In all cases localised information storage and processing methods make it difficult to link across to wider systems.

The enlightened organisation recognises maintenance as a prerequisite to production or service provision. Since the effectiveness of corporate objectives is seen as dependent upon maintenance, a different approach is taken to organisation and integration. Planning commences with integration as a starting point instead of trying to paste together disparate entities. This approach quickly identifies duplication and dissonance, and enables the parts of an organisation to work to the same objectives. The technological advances can realise their full potential only in this framework.

It is estimated that the penetration of condition monitoring (CM) is only 10–20% of its potential. This represents a loss of up to £1.6 bn in the UK alone [1]. One of the limiting

factors is the existing level of systems integration. This can be addressed by the holistic approach and the adoption of new technology, e.g.:

- open, global electronic information systems;
- adaptive, shared communications media;
- smart sensors;
- adaptive, flexible decision-making algorithms.

True integrated systems require top-down system design, which is able effectively to incorporate the elements above. The integrated system closes the loop from the minutiae of data collection to strategic decision making.

1.1 Levels of Integration

Integration theory combines the application of holistics and global performance criteria. The concept of asset management optimises labour, tools, equipment, materials, and information by integrating financial, human resources, and purchasing functions, as well as production, materials requirements planning, and enterprise resources planning systems [2]. The manufacturing systems community regards maintenance as a critical part of life cycle support, and facilitates this with software tools for design, implementation, run-time and change processes [3]. The integration of operations and maintenance is becoming widespread and is promoted by the use of Reliability Centred Maintenance (RCM) and Total Productive Maintenance (TPM) philosophies [4].

The information systems solutions are being driven by Enterprise Asset Management (EAM) in manufacturing, e.g. at Nippon Steel [5]. The integration of EAM and computerised maintenance management systems (CMMS) aims to prolong and enhance equipment and tool life, and reduce maintenance costs.

1.2 The technology of integration

Several enabling technologies have penetrated the maintenance sector. Hand held personal computers and bar code readers, coupled with the integration of work processes and systems, have enabled a cultural change [6]. Intelligent instruments merge control and maintenance, allowing field tasks to be performed from the control room [7]. In

complex systems such as gas turbines, the monitoring of health, cost, performance and remnant life is achieved with the integration of advanced diagnostics and models of structure and performance [8].

Multimedia resources have been adopted for maintenance, diagnostics and training [9]. Maintenance and process information are linked on the factory floor [10]. Fieldbus systems and virtual devices have been exploited for remote monitoring, maintenance and control, allowing a distributed systems infrastructure [11].

1.3   Applications of integration in maintenance

Integration in maintenance systems is of vital important in many industrial sectors:

- Electricity distribution: integration of control, quality, scheduling and maintenance over a SCADA in high and medium voltage networks [12]; remote on–line monitoring of electricity substations [13];

- Manufacturing: integration of data collection and statistical process control with cell control, diagnostics and planned maintenance in semiconductor manufacture [14]; integration of maintenance modules and diagnostics in flexible manufacturing systems [15];

- Power generation: integration of operations, engineering, and maintenance by providing data and software applications in a common environment [16];

- Military applications: very high levels of integration in weapons support, integrating display, modular instrumentation, information bank and diagnostics [17]; Helicopter Usage Monitoring Systems (*HUMS*) are well advanced [18];

- Rail: US operator Conrail integrates wayside monitoring devices with maintenance systems to detect faults in freight cars and reduce manual inspection requirements [19].

In terms of technology, thermography has been integrated with lubricant analysis, wear debris and contaminant analysis, and performance monitoring, to tackle the problem of "machine wear" in a holistic sense [20,21]. For example, integration of process information with expert system vibration analysis and wear debris analysis improves the

accuracy of fault detection in rotating machinery fault detection in air conditioning plant [22].

1.4   Consolidating the integration strategy

The review above shows that the islands of integration, mainly found at a technological level, are beginning to be merged. While the technologies enable some quantum leaps to be made, the vision must be formed at the top level. The strategic approach focuses the effort and raises the importance of maintenance.

This paper examines the structure and detail of some of those enabling technologies, and identifies what systems exist to achieve integration in maintenance. The structure and methodology which supports integration is described, and a globalised model is proposed. Examples are given of implementations of the levels of integration.

2.   Systems in maintenance engineering

Maintenance forms only part of a production or service operation. To form a picture of the systems, it is necessary to take a global view, as is done in top down design for systems. Here the specification of the system meets the required business objectives, and the operations and maintenance must fit with them. At the top level we find business oriented systems. Maintenance management sits below the business systems, and in a traditional organisation sits alongside production. In an integrated business, maintenance is part of the production organisation. Condition monitoring and control systems necessarily fit below plant operations and maintenance management.

2.1   Business systems

All manufacturing and service operations use their resources with the prime aim either of making money, or of providing an excellent service. Typical business systems manage transactions involving some or all of buying, processing, adding value, selling, and employment, and information pertaining to these. Almost all operations require physical assets, to perform the processing and/or to house the activity. The physical assets are

essential to the business, so the life cycle of those assets, and the cost associated with them, is fundamental to the success of the business.

Before we even consider a maintenance plan, several important decisions have usually been made:

- the purpose of the business associated with the assets;
- the risk associated with investing in the assets;
- the required output of the assets and hence pay back.

Even in less enlightened businesses, the information regarding acquisition of assets, production output, purchase of spare parts, and emoluments to the maintenance trade force resides in the business systems. Maintenance has a direct effect on the ability of the resources to be effective, and hence at least part of its management is always found in high level business systems.

In integrated business systems where maintenance is freely regarded as a prerequisite to production (e.g. by adopting the TPM philosophy) a good deal more of the activity of maintenance management finds itself at the top level in the hierarchy.

2.2   Maintenance management

Maintenance is the process of restoring an asset to full working order, or ideally, preventing it ever from leaving full working order, provided that it is economical to do so. Maintenance policy can be formed from the generic strategies of on-failure maintenance, time or usage based planned preventive maintenance (PPM), and condition based maintenance, and may incorporate hybrid planning based on asset operating windows. Repetitive failures may be designed out.

Typical maintenance systems plan maintenance around the following structures, which are commonly computerised.

- **Plant inventory/asset register** - an identification scheme is essential to the system.

- **Job catalogue** - time based PPM tasks are stored as a "tool kit" which is applied to the plant;

- **Work planning** - scheduling jobs and matching required skills to resources;

- **Stores** - catalogue of spare parts in stock, ordering information - over 10,000 items is common;

- **Report generation** - important for day-to-day running tasks and performance summaries;

- **Plant history** - feedback information is very important; unless recorded at the time of the incident, accurate information is forgotten. It is particularly useful to be able to compare the history of a group of similar machines.

2.3   Condition monitoring

Condition based maintenance (CBM) bases actions on the degradation of a parameter indicative of machine health. Regular PPM repair or replacement tasks are substituted by inspection and measurement. Condition monitoring (CM) is the assessment of plant health. The use of CBM shifts the focus away from maintaining plant to sustaining the ability of the plant to produce.

CBM provides the following benefits:
- Advanced warning of failure is given, so that repairs can be planned out of production time;
- Inconvenient breakdowns and expensive consequential damage are minimised;
- The failure rate is reduced, thus improving plant availability and reliability;
- A reduced spares inventory can be carried;
- Unnecessary work is avoided.

The CM parameter may be a performance indicator, or a diagnostic measurement which gives early warning of deterioration, e.g. vibration, thermal emissions, or oil analysis. Additional information is available from control and monitoring systems which offer

performance data from existing sensors or extra sensors, chosen to detect machine condition or process performance.

The success of a CM application depends as much on its financial performance as its technical performance. It is expected that a CM technique is sensitive enough to give adequate warning time before failure, and to have a clear change over the normal effects of noise on the data (through variation in measurement or performance). Additionally the costs of set up and operation should be exceeded by the savings in maintenance and indirect benefits.

Typical state of the art systems include on line measurement, and several different measurement techniques. Advanced systems also improve cost effectiveness with portable instrumentation. Examples include:

- Power stations monitor vibration, thermal emissions and lubricants using on– and off–line techniques. Steam turbines, for example, contain large masses rotating at high speed. If a turbine blade is shed, the unbalanced forces are considerable. The machines are monitored for vibration with hard wired accelerometers and displacement transducers which are continuously monitored. Excessive vibration can trigger immediate shutdown to prevent catastrophic damage.

- Paper machines have been monitored with hard wired accelerometers and shock pulse transducers, but it may be more cost effective to use portable instrumentation. The instrument is used with either portable or permanently mounted transducers. The data is transferred to a host computer at the end of the data collection tour.

- Electrical distribution, both high and low voltage, can be monitored on–line with thermal imaging. Many users hire a service rather than own the equipment, but retain ownership of the data. The data is used to diagnose potential faults and to schedule remedial action at a convenient time.

2.4   Plant Control

Control exercises regulation, verification or constraint, and determines the course of action. As a parallel to maintenance, which sustains the ability of the plant to produce, the

focus of control systems is to ensure production to the specified quantity and quality while meeting constraints.

Modern control systems tackle the disparate aspects of sequencing, where steps are made through state space, and of analogue control. Typical example applications are found in automation:

- The tool changer of a machining centre passes through approximately 20 discrete steps to exchange a tool, some of which depend on completion of a previous step and inputs from sensors;
- The temperature of a soldering vessel is required to be kept within a tight band, by continuous variation of the heater current, in response to reductions in temperature caused by dynamic changes such as work load and ambient conditions.

State of the art automated systems are able to communicate performance information to a supervisory system and to respond to requests for changes as required by systems higher in the hierarchical structure. Controllers interface with many forms of input and output, in modular fashion, and with many types of sensor as input. Considerable local processing capacity is provided, allowing distributed systems to act robustly and autonomously, and to realise complex control algorithms which are dependant on high speed data processing.

The indicators of good performance in a control system are associated with its ability to keep within a tight tolerance band in relation to the set point, and its ability accurately to track changes in the input with a minimum delay.

2.5   Systems comparison

Maintenance and control systems share many similarities at macroscopic and microscopic level, as illustrated on figure 1:

- their hierarchical structures, which pass messages and requests down to the plant, and return signals and information to higher levels of supervision;

- the technologies of communication and measurement, e.g. data acquisition, signal processing including trending and abnormality detection, data storage, and subsequent data mining.

Some fundamental differences exist, of course. In CM applications the result of monitoring is planned actions. A relatively loose feed back loop exists, usually with human intervention. The time scales allow hours, days, or preferably months of lead time. Short term guaranteed delivery of messages is rarely required. The actions are proactive, intending to avoid an unplanned failure.

In control, on the other hand, the time scales are "real time" i.e. of a short time constant down to fractions of a second. Many signals need guaranteed delivery times. There is less emphasis on system history unless the system is model based. The focus is on production, hence different sub-business objectives exist. Automatic actions require a tight control loop but its nature is reactive to external conditions.

3. Integration: conceptualisation and exploitation of enabling technologies

Considerable steps forward are being made in systems integration in maintenance and control as a consequence of conceptual and technological advances. Concepts are drawn from complementary areas of manufacturing and IT. New technologies are providing off–the–shelf solutions to problems for which, historically, the control and CM communities have reluctantly developed bespoke solutions at great expense. Hard–wired data collection, for example, has been a source of chagrin to the industry.

Massive leaps in low cost computer processing power and memory enable powerful numerical algorithms to be performed, in some cases using mathematics which has existed for many years but impossible to realise outside research laboratories. Fast communications allow high bandwidth signals to be transferred at high sampling rates and to tighten the performance of control loops. Local processing can turn data into

information, decimating the data rate. Smart sensors take this a step further, moving the decision making algorithm down to the sensor, and only communicating with the wider system when necessary. Standards, whether official or *de facto*, offer working solutions such that the control and CM specialists can concentrate on their own fields rather than reinventing the wheel.

3.1 Integration overview

Integration is the unification of the parts into a coherent whole. In maintenance the motivation for integration is the wish to reduce the number of separate systems, to increase automation and to reduce manning. In integrated systems the overall architecture is important, because the traditional boundaries are blurred or removed entirely. The communications process during design and implementation is most important, because it ensures that the people concerned are brought "on board" – there is a danger of alienation, which creates its own barriers and conflicts.

The success of integration in systems can be measured by a number of performance criteria:

- Avoidance of duplication: shared information, reduced effort;
- Greater robustness and reliability;
- Tighter loops in the broad sense of control: less effort for the same gain or more output for the same input;
- A "total" approach improves many human/management issues.

The emergent generation of factory automation systems comprises five key components:

- field devices (sensors);
- final control elements (actuators);
- process control units;
- condition monitoring systems;
- management support systems.

The existing distinction between control and maintenance systems is disappearing. Intelligent field devices will replace existing analogue sensors. These feature two-way digital communication in addition to a degree of local intelligence, permitting them to make decisions and to perform signal processing tasks. The information obtained from the field devices is used by the process control unit as the basis for closed-loop control. The condition monitoring system will perform its conventional tasks (e.g. data trending, abnormality detection) but it may also utilise process control system data as an additional source of condition-indicating information.

3.2   Current advances

The pressures upon manufacturing industry to reduce production costs and to improve operational efficiencies have never been greater. The improvement of performance is essential to ensure survival. The magnitudes of these pressures seem inexorably linked to the rate of technological advancement.

Recent years have seen the proliferation of sophisticated automatic control, condition monitoring and manufacturing systems. The cost of the microelectronic components continues to fall, and digital electronics is now permeating the sensors, actuators, transmitters, and drivers of industrial control equipment.

These items, which were previously seen as discrete entities, are being linked by digital networks to permit communication between in-the-field devices (digital sensors and actuators) and the higher-level components (such as PLCs) of the automation system. Currently there exists a diversity of proprietary standards governing the rules for communication between the devices, and as a consequence the resulting networks are often incompatible, meaning that individual users find themselves forced into sourcing automation equipment from a single supplier.

The need for an open, rigorously defined, non-proprietary communications protocol has led to the formation of industrial "clubs" which aim to standardise the rules of

communication so that devices from many vendors may be plugged directly into a factory floor network without extensive configuration.

These technological advances would be of little interest to a maintenance engineer if they did not offer exciting potential for access to, and sharing of, condition-indicating data. They bring with them the realistic possibility that signals from a wide range of existing control system sensors (like thermocouples, pressure transducers and proximity probes) may be combined with those from devices specifically installed for CM purposes (such as accelerometers). This multivariate data can then be fused to improve condition indicating information and consequently to enhance maintenance management decision making.

There are three factors which are currently advancing integration:
- standardisation – the modularization of hardware and software, and *de facto* commonality;
- human issues – the technology of system design and realisation is becoming more widely accepted and skills are being developed;
- cost – the reduction in acquisition and upgrade cost associated with a widely applicable and accepted technology.

3.3   Structure, design methods and tools

In many areas of manufacturing management structured methods are used to define problems and plan solutions [23]. For example, in computerised information systems, structured methods for design use modelling, definition and analysis techniques, such as SSADM (Structured Systems and Design Methodology) or IDEF (ICAM (Integrated Computer Aided Manufacturing) Definition). The following characteristics are common [24]:
- A project is structured into small, well defined activities; the sequence and interaction of the activities is specified.
- A diagrammatic or other modelling technique defines the structure.

The approach in software design is a similar discipline and identifies data flow as a logical tool for understanding and working with a system of any complexity [25]. Structured methods in Manufacturing Systems extend further than the original concepts of information systems design, and are penetrating many areas of selection and design processes. In maintenance, formalised methods are being created which are partly embodied in reliability centred maintenance (RCM) [26]. These procedures aid the decisions in selection and design of a condition based maintenance programme by using a consistent scheme which:

- defines the known information in a criticality analysis and a maintenance audit, i.e. defines the problem;

- selects plant, and performs a further analysis using failure data or heuristic failure analysis, before matching techniques to failure mode, i.e. selects a solution;

- enforces review processes to evaluate effectiveness at all levels.

In control it is common to use a block diagram representation prior to modelling, and this is also useful for reliability block diagrams [27]. In holistic approaches, however, the control and monitoring community can gain considerably by taking a wider approach, as exemplified by the use of the Boyd control loop in data fusion architectures [28]. The structure loops through the stages of observation, orientation, decision and action (OODA). In monitoring and control terms, these align as shown in figure 2. While the OODA loop was conceived for military control, it has found enthusiastic followers in business strategy and encapsulates many desirable features for integrated system design.

3.4   Emerging standards

3.4.1   Fieldbus

The construction of a distributed control and monitoring system is enabled by an accepted set of communications rules or *protocol,* e.g. Fieldbus. It is the basis for an advanced networking system used to interconnect field devices such as sensors, actuators, and transducers to higher level systems such as PLCs for control or microcomputers for monitoring purposes. Unlike computer network protocols (e.g. Ethernet) Fieldbuses are optimised for the exchange of relatively short data messages containing control or status

information. They can guarantee delivery of messages on a periodic basis or within a limited time. Fieldbuses transmit digital signals along a twisted pair cable, and are replacing the traditional 4-20mA analogue network system. The advantages include:

- digital signals are more robust in the presence of noise;
- cabling costs are substantially reduced because all devices are linked up on the same cable;
- modularity, allowing reconfiguration and upgrading;
- novel interaction between devices.

Fieldbus enables two-way communication with information no longer being addressed to specific areas of the network but being available to all nodes. This allows full advantage to be taken of existing information, empowering intelligent field devices and leading towards distributed control.

A true Fieldbus has the ability to pass information across contractual boundaries, not just within automation systems, but both down into the plant equipment and up into the factory–wide management information system (MIS). The demand for information is subject to change and has to be extracted without disturbing the real-time control. It is therefore necessary that the Fieldbus not only prevents disturbance of time-critical traffic by messages, but that the unexpected traffic can be handled with no change to the original application software.

This is where the "producer-consumer" model of communications is of key importance. This allows any node on the network to consume the data that is already passing without any disturbance to the network traffic. So, for example, it is simple to add a SCADA system or gateway to "piggy back" on a PLC/remote I/O network without changing the PLC programme or disturbing the control. It is only possible to have open "hooks" with networks using a producer-consumer model. For those using master-slave communications it is necessary to work through the master or add additional communications traffic.

There are three major international Fieldbus clubs, each of which started in a different country and is supported by different major suppliers:

- Foundation Fieldbus (USA: the major DCS manufacturers)
- Profibus (Germany: Siemens)
- WorldFIP (France: Alstom, Cegelec, Groupe Schneider/Telemecanique)

An International Fieldbus, IEC 61158, has been under development for many years. It is a layered communications protocol with three layers: Physical, Data link and Applications. The physical layer (cable, connectors, electrical signalling) has been a standard for over 5 years. The data link and applications layer have been approved and are likely to come into use in the next 5 to 10 years.

There are many other proprietary protocols which claim to be a Fieldbus. There is also a European Standard, EN50170, issued by CENELEC, which includes WorldFIP, Profibus and P-Net as three solutions for general purpose field communications. The Fieldbus standardisation process has recognised the need to support background messages for configuration, diagnostics and condition monitoring. This is reflected strongly in the IEC Standard and in WorldFIP.

3.4.2   Other emergent standards

Whilst Fieldbus is creating a sea change in control architectures, several emergent standards are influencing the use of data at higher level in maintenance and control. Among these, MIMOSA, STEP and OPC have significant impact.

The Machinery Information Management Open Systems Alliance (MIMOSA) advocates open exchange of equipment condition related information between condition assessment, process control and maintenance information systems through published and consensus conventions. This will gain its greatest value by combining condition information from multiple sources for collective evaluation, reaching accurate determinations of current condition and remaining life and communicating results in a useful, understandable form at a managerial level [29].

The Standard for the Exchange of Product Model Data (STEP) is the familiar name for ISO 10303 [30]. STEP is developed by the working committee for ISO TC184 SC4, Industrial-Automation Systems and Integration, Industrial Data. STEP is the result of many years development in product data management (PDM), which offers huge advantages for the manufacturing sector, and hence has many parallels with maintenance and control.

Object linking and embedding (OLE) for process control (OPC) is an emerging software standard designed to provide business applications with easy and common access to industrial plant floor data [31]. Traditionally, each software or application developer was required to write a custom interface, or server/driver, to exchange data with hardware field devices. OPC eliminates this requirement by defining a common interface that permits this work to be done once, and then easily reused by management and control applications. OPC has significant influence on the workings of Fieldbus protocols and on the MIMOSA standards.

3.5   Integration benefits

The enhanced processing and decision making capabilities offered by an integrated maintenance and control system using a distributed architecture bring three powerful benefits to maintenance and monitoring systems:

- increased processing power;
- distributed processing, which localises intelligence near to (or within) the sensor;
- shared information between sensors and the conceptually high level system components.

There are many opportunities to apply these capabilities, some of which are discussed below.

3.5.1 Data fusion and multivariate trending

Data fusion is the process of combining data and knowledge from different sources with the aim of maximising the useful information content, for improved reliability or discriminant capability, whilst minimising the quantity of data ultimately retained [32].

The sensor and signal processing communities have been using fusion to synthesise the results of two or more sensors for some years. This simple step recognises the limitations of a single sensor but exploits the capability of another similar or dissimilar sensor to calibrate, add dimensionality or simply to increase statistical significance or robustness to cope with sensor uncertainty. In many such applications the fusion process is necessary to gain sufficient detail in the required domain.

Higher levels of data fusion deal with problems of feature extraction, correlation, and decision making. A common structure can be identified, which can be compared to the Boyd loop, and is embodied in the Joint Directors of Laboratories (JDL) model as shown in figure 3 [33]. In real problems, it is not always necessary to apply all the stages:

- Pre-processing, i.e. reduction of the quantity of data whilst retaining useful information and improving its quality, with minimal loss of detail. The pre-processing may include feature extraction and sensor validation. Some of the techniques used include dimension reduction, gating for association, thresholding, Fourier transform, averaging, and image processing.
- Data alignment, where the techniques must fuse the results of multiple independent sensors, or possibly features already extracted in pre-processing. These include association metrics, batch and sequential estimation processes, grouping techniques, and model-based methods.
- Post-processing, combining the mathematical data with knowledge, and decision making. Techniques could be classified as knowledge-based, cognitive-based, heuristic, and statistical.

Classical condition monitoring systems treat monitored parameters individually by trending processed results from single sensors (single values or spectral arrays) and relying upon the maintenance engineer to interpret them in combination. The intelligent sensor can take many transducer readings and share this information with other sensors. The combined data can be fused to produce a multi-dimensional representation whose trends and variations provide much more powerful condition indicating information. For example, in the case of rolling element bearing damage, rises in bearing frequencies may be accompanied by impact excited resonance and a lagged rise in housing temperature, measured by an accelerometer and a thermometer respectively. By mathematical manipulation these three data forms from the two sensors can be fused to produce a powerful multivariate indicator.

3.5.2   Smart Sensors

A smart sensor, or intelligent field device, has several elements which make it superior to a conventional sensor. It may contain some or all of the following parts, which traditionally have been part of a wider system. "Smart" does not imply miniature, but many of the functions described can be included on a single printed circuit board, or where mass production allows, on a single chip.

- Sampling: traditionally controlled by the host, the on–board algorithm of a smart sensor can dictate when and how the signal is sampled.

- Processing and memory: the computing power to perform signal processing has traditionally been expensive, leading to high bandwidth data acquisition systems and centralised processing. The high bandwidth cabling is now one of the most expensive items to buy and install. Local processing can reduce data transmission and speed up response. Complex signal processing can be performed on raw data without transmission across a data network. Data can be stored until transmission is instructed or requested remotely.

- Communications interfaces: integrated 4–20mA interfaces are commonplace, but the smart sensor can also include and control a wireless transceiver, modem, Ethernet adapter, Fieldbus node or internet host. Bi–directional communication is necessary to

allow the host to send instructions, and for the sensor to return status information or data.

- Decision making: the on board algorithm can control any function, e.g. whether or not to transmit data, and how much.

- Calibration: local measurement of conditions can be used for correction and compensation prior to data transmission.

- Redundancy: multiple sensing elements can be incorporated in a single smart sensor, to increase dimensionality or to validate the measurement. This can account for drift or rogue readings at the point of measurement.

3.5.3 Robustness

Hard-wired condition monitoring systems are susceptible to sensor failure and damage to cabling. Automation systems are frequently and unnecessarily shut down due to erroneous information received from sensors. Within a Fieldbus based system it is possible to incorporate sensor validation mechanisms. Such mechanisms exploit the redundancy between nearby sensors and permit validation of sensor output and data reconstruction in the event of a device failure.

The use of intelligent devices permits prioritisation of the information that they are generating, or its storage until the transient overload has passed. This avoids the inherent drawback of conventional serial process control and monitoring systems.

3.5.4 Model-based fault diagnosis

Model based fault diagnosis uses a mathematical model of the plant as the basis for decision making. The model may be updated on-line by using information from sensors and the control system. Changes in the plant model may then be related to variations in the condition of the plant. The influence of sporadic sensor noise is greatly reduced because the model is tolerant to transient variation. Model based fault diagnosis is a powerful aid to condition monitoring. In industrial applications model updating has been used in control but rarely for CM.

3.5.5 Scalability

The design framework must be flexible and adaptable. Modular designs can evolve. The ability to reconfigure hardware and software components is important. For example it may be necessary to add a CM module to an existing automation system. A distributed architecture not only allows the future addition of more processing power, but permits optimisation of the individual processors according to the specialist tasks that each must perform.

3.5.6 Future proofing

Distributed systems are open to evolutionary change. The automation system manufacturers benefit from a steady demand for more advanced components, while adherence to standards allows them to focus design activity.

Often, instrumentation is replaced because its accompanying software has less functionality than newer products, or because of changes in the processing to be performed on the sensor data. Re-programmable sensors allow remote software updates to field devices, enabling the incorporation of new processing techniques and advances in maintenance technology. This can be achieved with minimum disruption to system operation and no changes to system hardware.

4.   Exemplars

The best examples of integrated systems to date comprise the elements which suit particular applications. Each integrated system is different, and hence develops and exploits differing aspects. The examples below demonstrate integration at several levels:

- Management systems;
- Decision–level fusion;
- Condition monitoring over a Fieldbus network;
- Advanced signal processing algorithms for feature extraction on a smart sensor.

4.1   Integration of management information systems

Many management information systems (MIS's) are encountered in maintenance management. In building services maintenance at a major London Bank, the Facilities Management System (FMS) is perhaps the top level in MIS [34]. A typical FMS, in common with the typical MIS in many other sectors, includes modules for:

- resources: plant and spares inventory, personnel, skills, tools;

- suppliers and customers, cost estimating, purchasing and billing;

- planning and scheduling, activities, installations;

- reporting and graphical output;

- historical analysis and forecasting.

The FMS is commonly installed on one or more workstations accessing databases over a technical network. As an MIS it is not intended to gather information directly from hardware, nor to transmit instructions to it. The FMS can be considered complementary to the maintenance management system (CMMS) and building energy management system (BEMS). The FMS deals with the management functions, the CMMS deals with monitoring and maintenance actions, while the BEMS deals with the control issues. There are, however, areas of overlap and information exchange:

- all systems require a plant inventory structure for identification;

- the BEMS can generate valuable utilisation and costing information for the FMS;

- the FMS may contain scheduling information which will be used to program the BEMS;

- the CMMS can collect jobs from the FMS and data from the BEMS, and transmit costing information to the FMS.

As an example of the information which the BEMS can pass to the FMS, figure 4 shows a sample of the services consumption data in a large building complex. The BEMS was programmed to summarise consumption of electricity, gas and water on a daily basis. The information was passed through a spreadsheet, which allowed live updating through DDE, as well as bespoke analysis and charting. This information was in turn used for billing the building users.

The BEMS usually handles data from building systems such as electrical power, transportation and heating, ventilation and air conditioning (HVAC). At another building a BEMS outstation was fitted with a smart interface to allow high–bandwidth vibration signals to be sampled. Figure 5a illustrates the schematic for interfacing vibration data collection to the BEMS and figure 5b shows a typical report.

4.2 Knowledge based decision fusion

In complex systems we make decisions based on measured parameters, but we relate those to knowledge about the way the systems operates. In manufacturing systems, for example, operational faults account for about 70% of failures. Rapid diagnosis is critical for improving the availability and productivity of the manufacturing system.

Diagnosis of complex systems is challenging because there are many different faults, and training is likely to be forgotten before it can be applied. Hierarchical diagnosis models, based on fault tree analysis, logical control and sequential control can be built around the operation of the Programmable Logical Controller (PLC). With these models working together, the operational faults of a manufacturing system can be diagnosed completely. The models have been successfully applied to a PLC controlled flexible manufacturing system and have achieved good results [35].

The model combines knowledge about the intended operating procedure with measured inputs from the normal automation sensors. The stage of the programme indicates the broad area of the fault, and the status of the measured inputs localises the solution further. In the example shown in figure 6, a system fault in a flexible manufacturing system (FMS) is traced:

- In the functional tree, we first establish that the FMS has failed because of a machine tool (F11); the tree further establishes that this is a PFZ1500 milling machine (F21); this has failed during the machining process (F33).
- According to the principles of operation of the machining process (P11), the highest probability lies in a spindle failure (P21: 0.4) and that, in this case, the most likely fault is the spindle motor (P32: 0.45).

- The rule tree analyses the potential faults in the spindle motor and their cost weighted risk. Here several potential faults are compared, and the most likely ones are investigated: a fault could exist in the mechanical drive system (R211) or in the control circuit (R212). A first likely fault is a high temperature cut out (R312) caused by a blunt tool (R421). Other likely faults are investigated in order of probability until the fault is found.

4.3   Condition monitoring over Fieldbus with intelligent sensors

A Fieldbus network was constructed at the University of Manchester to demonstrate the use of smart sensors in condition monitoring. A PC was programmed to act as a combined bus arbitrator and CM controller, and another as a remote node and intelligent sensor. 50% of the Fieldbus bandwidth was deliberately occupied by the continuous transmission of simulated time critical control variables. On the Fieldbus between the two PC's a field tap was provided to permit a third PC to access the Fieldbus and transmit the data to an Ethernet link to an Internet server. The server provided world-wide real-time access to the condition monitoring of an induction motor in the Manchester laboratories and the functioning of the intelligent sensor as the motor's condition was changed on line. Figure 7 shows a schematic of the demonstrator system, and figure 8 shows the web page output.

The function of the CM controller was to implement the monitoring strategy. In overview, this involved requesting information from the intelligent sensor, interpreting this information, and issuing messages as necessary for consumption by the management information systems that would in reality be present on the same network. Specifically, the monitoring strategy was defined as follows:

- routinely request a condition status (i.e. a green, amber or red traffic light) from the intelligent sensor;
- if status is green, record status and time stamp, then wait 60 seconds until next status indicator is required;
- if status is amber, record status and time stamp, then request and record data summary, then reduce subsequent monitoring interval to 15 seconds;

- if status is red, record status and time stamp, then request and record full data transmission, then reduce subsequent monitoring interval to 15 seconds and issue a warning message onto the network for consumption by the management information systems.

There are numerous ways in which this monitoring strategy could be changed or refined. The system demonstrated 'on-request' communication of condition monitoring information over a Fieldbus network which was being used for the simultaneous transmission of time-critical data. In terms of the intelligent sensor, the prototype included simple signal processing:

- sensing, filtering and amplification of vibration acceleration data;
- sampling and digitisation;
- calculation of RMS level and frequency spectrum (FFT);
- comparison of processed output with thresholds;
- determination of the current status;
- on request from the condition monitoring controller, transmission of the status, time stamp, data summary or full FFT as necessary.

4.4   Advanced signal processing algorithms in an intelligent sensor

Analytical techniques can accentuate condition monitoring information by manipulating the data from measurements. In rotating and reciprocating machines it is common to use software or hardware to convert a time series of vibration data into the frequency domain. This has limitations in non–stationary signals because transient events are lost in the averaging. Time-frequency representations permit the simultaneous representation of a signal's time, frequency and amplitude on a per cycle or per revolution basis. [36]

Time-frequency methods are particularly useful in CM because many common machine faults give rise to transient vibration or electrical symptoms which are superimposed upon a continuous periodic waveform. The transients themselves may occur from impacting, stiffness variation around a cycle, or asymmetric magnetic effects. With the ability to interpret the output of advanced signal processing techniques such as these,

comes the ability to incorporate them within a stand-alone microprocessor system such as a smart sensor.

The example shown in figure 9 demonstrates the characterisation of a diesel fuel injector. Its characteristics are hard to identify in the noisy environment of the engine when using the time domain or frequency domain alone. In the time–frequency plot, however, it is possible to detect the timing events, including the opening and closing of the injector needle, the onset and duration of combustion, and the peak acceleration level, which is well correlated with the maximum pressure in the cylinder. The time–frequency plot has sufficiently high resolution to identify faults in injection and timing.

5. Conclusions

5.1 Integration in maintenance engineering
Systems integration in maintenance exists on many levels, from the business system right through to the sensor. Many new technologies are providing rapid routes to advances in integration and allowing the realisation of existing and novel integration theory. A fundamental aim of maintenance activity is to deliver a required level of service from plant at the lowest lifecycle cost. Cost effective advancement in maintenance technology will be achieved by making better use of the data that is already held on a plant, rather than by measuring more variables.

5.2 Standards
The use of international and cross–industrial *de facto* standards is important to the ability of the manifold information systems found in maintenance engineering to communicate, and also to the effectiveness of off–the–shelf hardware and software. The adoption of standard information exchange protocols allows the system builder to concentrate on maintenance related issues rather than being diverted into IT and data acquisition problems.

5.3 Enabling technologies

Next generation automation systems will be more open, integrated and robust than their predecessors. With a communications backbone provided by internationally agreed protocols, information will be shared between the control, maintenance and process management systems which will allow improved plant utilisation through more effective control and better informed decision making. Fieldbuses are now being widely used for control and instrumentation, and have shown potential for use for condition monitoring.

5.4   Advanced processing

Distributed processing is considerably enhancing the capacity to integrate and evolve advanced algorithms, which are tending to run close to the source of the data rather than in a centralised system. The low cost, speed and memory capacity of distributed processing, down to sensor level, now allows the use of algorithms such as the time–frequency transforms which have up to now been restricted to high speed devices in the laboratory.

5.5   Architecture

The most significant influence on the success of integration is the overall vision. While the detail of every step must be in place, and each part contributes to the whole, the formation of a strategic picture of maintenance as part of the business is required to make sense of the purpose of integration down to sensor level. The architecture will be the embodiment of a holistic approach.

5.6   Future directions

Examples of the levels of integration have been shown which demonstrate performance benefits, both on a technical and business level. Considerable work remains to be done to realise fully integrated systems over all the potential levels, but a major effort will be in convincing users that their commitment to new standards and protocols is worthwhile. Change will be evolutionary: users own many "legacy" systems, and suppliers have a commitment to existing products which do not yet take advantage of all of the potential benefits. Sustained collaboration and standardisation will be essential.

6. Acknowledgements

The authors would like to thank the following bodies for their support and collaboration:

7 References

[1] Kennedy, I, 1998, Holistic Machine Condition Monitoring, *Seminar – Advances in Maintenance Engineering,* University of Manchester

[2] Dilger KA, 1997, Asset management, maintenance redefined, Manufacturing Systems, Vol.15, No.7, pp.122-124, 126-128, ISSN 0748-948X

[3] Singh V, Weston RH, 1996, Life cycle support of manufacturing systems based on an integration of tools, International Journal of Production Research, Vol.34, No.1, pp.1-17, ISSN: 0020-7543

[4] Marquez RB, Burgess J, 1998, Introduction of reliability centered maintenance in a copper smelter, Proceedings of the 1998 TMS Annual Meeting, San Antonio, TX, pp.197-203, (Conf. code 48105)

[5] Weil M, 1998, Raising the bar for maintenance applications, Manufacturing Systems, Vol.16, No.11, p.5, ISSN: 0748-948X

[6] McElhaney D, Aelmore J, Braun G, 1997, Use of hand held bar code readers and personal computers to improve plant maintenance, Proceedings of the 1997 76th Annual Convention of the Gas Processors Association, San Antonio, TX, USA, Mar 10-12 1997, (Conf. code 46983), ISSN 0096-8870

[7] Chemane LA, Nunes AF Jr, Hancke GP, 1997, Industrial information infrastructure and intelligent instrumentation - the options, Proceedings of the 1997 IEEE International Symposium on Industrial Electronics, Vol.1, pp.44-48, (Conf. code 48073)

[8] Roemer MJ, Atkinson B, 1997, Real-time health monitoring and diagnostics for gas turbine engines, Proceedings of the, 1997 International Gas Turbine & Aeroengine,

Congress & Exposition, Orlando, FL, American Society of Mechanical Engineers ISSN: 0402-1215 (Conf. code 47341)

[9]   Crowder RM, Hall W, Heath I, Bernard R, Gaskell D, 1996, Hypermedia maintenance information system, Computing & Control Engineering Journal, Vol.7, No.3, pp.121-128, ISSN 0956-3385

[10]   Crowder RM, Hall W, Heath I, Wills G, 1999, Integration of manufacturing information using open hypermedia, Computers in Industry, Vol.38, No.1, pp. 31-42, ISSN 0166-3615

[11]   Lumpp T, Gruhler G, Kuechlin W, 1998, Virtual Java Devices integration of Fieldbus based systems in the Internet, Proceedings of the 1998 24th Annual Conference of the IEEE Industrial Electronics Society, IECON. Part 1 (of 4), Aachen, Ger, Aug 31-Sep 4 1998, (Conf. code 49499), Vol.1, pp. 176-181

[12]   Grosmangin F, 1997, Diagnosis of the location of defects accessible from an MV network control system (SCADA), Proceedings of the 14th International Conference and Exhibition on Electricity Distribution, CIRED. Part 1/4 (of 7), Birmingham, UK, Jun 2-5 1997, (Conf. code 47479), IEE Conference Publication, 1997, No.438 pt 1/4, pp.4.28.1- 4.28.3 ISSN: 0537-9989

[13]   Chan WL, So ATP, Lai LL, 1999, Internet based transmission substation monitoring, IEEE Transactions on Power Systems, Feb 1999, Vol.14, No.1, pp. 293-298, ISSN: 0885-8950

 [14]   Clayton M, Durham J, Felker S, Fortner G, Martinez J, Shelton S, 1997, Manufacturing integration of data collection and statistical process control systems, Proceedings of the 1997 IEEE 6th International Conference on Emerging Technologies & Factory Automation, ETFA, (Conf. code 47152), Los Angeles, CA, pp.505-507, IEEE, Piscataway, NJ, USA

[15]   LopezDeLacalle LN, Zulueta G, Burgos A, Sarachaga I, Fernandez H, 1997, Integracion del mantenimiento en la filosofia de control de sistemas automatizados (Integration of maintenance in the philosophy of automized system control) Informacion Tecnologica, Vol.8, No.1, pp.17-22, ISSN: 0716-8756

[16]   Wood RT, Mullens JA, Naser JA, 1997, Plant-window system: a flexible, expandable computing environment for the integration of nuclear power plant

activities, Proceedings of the 1997 5th International Conference on Nuclear Engineering, ICONE, p.263, ASME (Conf. code, 46894)

[17]   Bosco CD, Su LP, Girolamo H, Darty M, 1996, Maintenance and Repair Support System (MARSS), Proceedings of the AUTOTESTCON'96 Conference, Dayton, OH, (Conf. code 45491), pp.336-343, ISSN: 0734-7510

[18]   Legge PJ, 1996, Health and Usage Monitoring System (HUMS) in retrofit and *ab initio* helicopter applications, Proceedings of the 1996 52nd Annual Forum. Part 2 (of 3), (Conf. code 45377), American Helicopter Society, Vol.2, pp.1407-1417, Alexandria, VA, USA, ISSN: 0733-4249

[19]   Steets PG, Tse YH, 1998, Conrail's integrated automated wayside inspection, Proceedings of the IEEE/ASME Joint Railroad Conference, Philadelphia, PA, pp.113-125, IEEE, (Conf. code 48527)

[20]   Evans JP, Jarc TJ, Wurzbach RN, 1995, Increasing predictive program effectiveness by integrating thermography and lubricant analysis, Proceedings of Thermosense XVII: An International Conference on Thermal Sensing and Imaging Diagnostic Applications, Orlando, FL, SPIE - The International Society for Optical Engineering, Vol.2473, pp.82-90, ISSN: 0277-786X, 0-81-941826-9, (Conf. code 22196)

[21]   Ball PG, 1998, Machine wear analysis - a rational approach to methods integration for maximum benefits, Lubrication Engineering, Vol.54, No.3, pp.18-22, ISSN: 0024-7154

[22]   Martin DK, VanDyke J, 1997, Integrating vibration, motor current, and wear particle analysis with machine operating state for on-line machinery prognostics/diagnostics systems (MPROS), Proceedings of the 1997 ASME International Mechanical Engineering Congress and Exposition, Dallas, TX, American Society of Mechanical Engineers, Tribology Division, Vol.7, pp.61-67, (Conf. code 47756)

[23]   Report of EPSRC Workshop on Structured Methods and Tools in Information Systems Specification and Design, November 1995, Department of Industrial Studies, University of Liverpool

[24]   Goodland, M., Slater, C., 1992, <u>SSADM Version 4 - A Practical Approach</u>, McGraw Hill

[25]   Yourdon, E., Constantine, L.L., 1979, Structured Design, Prentice Hall

[26]   Moubray, J., 1997, Reliability centred maintenance (2 ed.) Butterworth Heinemann ISBN 0-7506-3358-1

[27]   BSI, 1986, BS5760 British standard - Reliability of constructed or manufactured products, systems, equipments or components

[28]   Boyd, J R, The Essence of Winning and Losing, http://www.belisarius.com/

[29]   MIMOSA, http://www.mimosa.org/

[30]   ISO 10303 - Industrial automation systems and integration - Product data representation and exchange, http://www.nist.gov/sc4/

[31]   OPC Foundation, http://www.opcfoundation.org/

[32]   Starr A, Desforges M, 1998, Strategies in data fusion - sorting through the tool box, Proceedings of Eurofusion 98 – DERA Malvern, UK

[33]   Starr A G, Esteban J, Desforges M, 1999, Strategies in Data Fusion - A Condition Monitoring Approach, Proc. 12th International Congress on Condition Monitoring and Diagnostic Engineering Management (COMADEM 99), Sunderland, UK

[34]   Starr, A, Wynne, R, Kennedy, I, 1993, Condition monitoring of building services - a case study in a high technology building, Proc. 5th International Congress on Condition Monitoring and Diagnostic Engineering Management (COMADEM 93), Bristol, UK

[35]   Hu W, Starr A G, Leung A Y T, Two diagnostic models for PLC controlled flexible manufacturing systems, International Journal of Machine Tools & Manufacture, Vol 39 Iss 12 pp1979-1991, ISSN 0890-6955

[36]   Gu F, Ball A D, Rao K K, 1996, Diesel injector dynamic modelling and estimation of injection parameters from impact response – Part 2: prediction of injection parameters from monitored vibration, *Proc. I. Mech. E. Part D: Journal of Automobile Engineering,* v210 pp303–312

Figure Captions

Figure 1:   Communications flow in integrated manufacturing, maintenance and control

Figure 2:   The Boyd control loop adapted to monitoring and control
               (*with acknowledgements to O'Brien and Bedworth)*

Figure 3:   The JDL model framework for data fusion

Figure 4:   Electrical services consumption data in a large building complex, recorded by the BEMS and transferred to the FMS

Figure 5a: Multiplexed vibration inputs to a BEMS outstation

Figure 5b: Monitored data from the BEMS

Figure 6:   A diagnostic reasoning procedure for a machine tool [35]

Figure 7:   Schematic of the demonstrator Fieldbus-based smart sensor

Figure 8:   Web page output from the demonstrator smart sensor

Figure 9:   Characterisation of a diesel fuel injector from vibration and cylinder pressure, displayed in time-frequency plots
               Engine FSD425 operating at 59.7Nm and 2043 rev./min.

Abbreviations

BEMS	Building energy management system
CAM	Computer aided manufacturing
CBM	Condition based maintenance
CENELEC	European committee for electrotechnical standardization
CM	Condition monitoring
CMMS	Computerised maintenance management system
DCS	Distributed control system
DDE	Dynamic data exchange
EAM	Enterprise asset management
EN	Euro Norm
FFT	Fast Fourier transform
FMS	Flexible manufacturing system *or* Facilities management system
HUMS	Helicopter usage and monitoring system
HVAC	Heating, ventilation and air conditioning
ICAM	Integrated CAM
IDEF	ICAM definition
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization (ISO)
IT	Information technology
JDL	Joint directors of laboratories (US military)
LAN	Local area network
MIMOSA	Machinery information management open systems alliance
MIS	Management information system
OLE	Object linking and embedding
OODA	Observe, orientate, decide, act
OPC	OLE for process control
PC	Personal computer
PLC	Programmable logic controller
PPM	Time base planned preventive maintenance system
RCM	Reliability centred maintenance

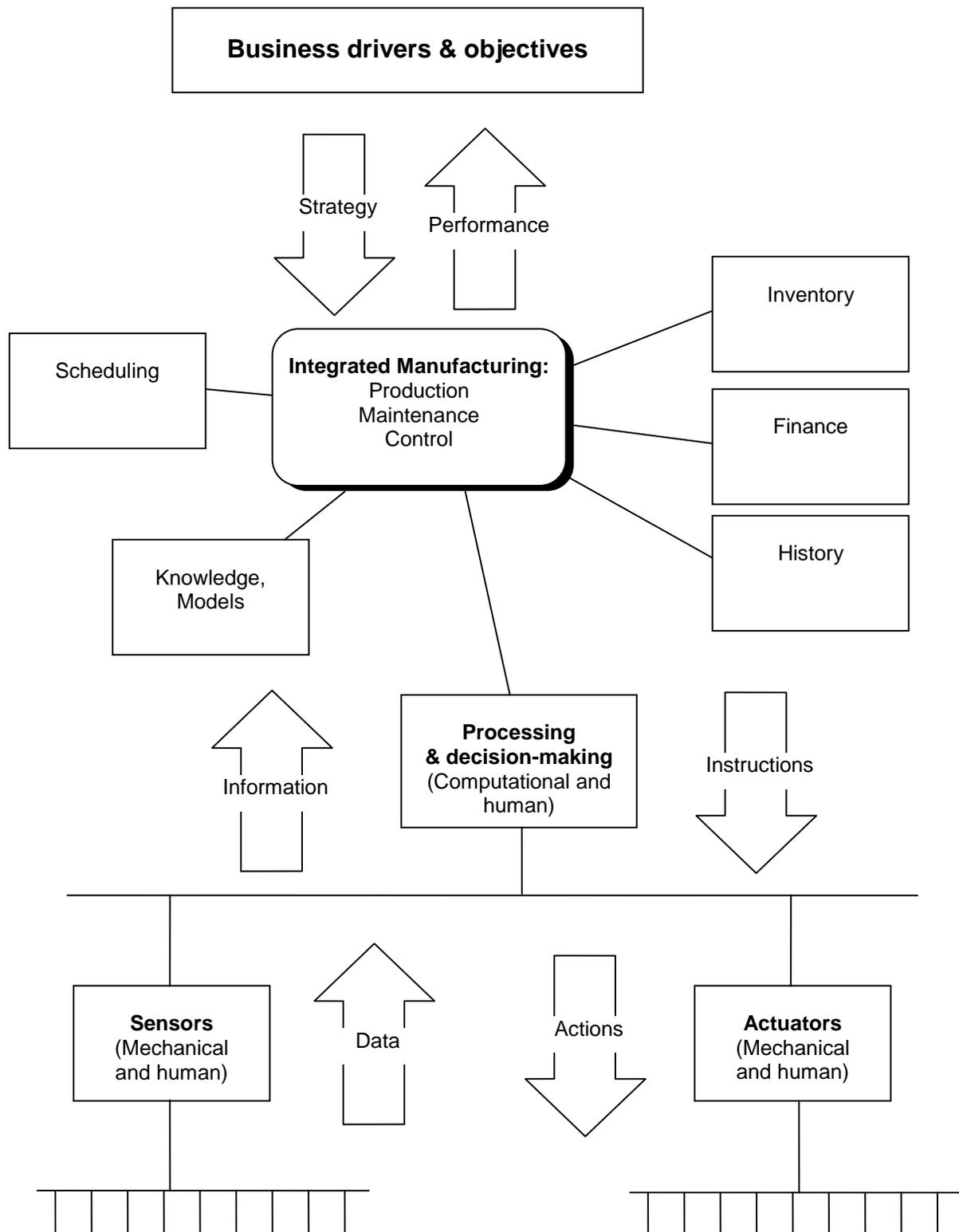| SCADA | Supervisory control and data acquisition |
SSADM	Structured systems analysis and design method
STEP	Standard for the exchange of product model data
TPM	Total productive maintenance
TQM	Total quality management

Business drivers & objectives

Strategy

Performance

Scheduling

Integrated Manufacturing:
Production
Maintenance
Control

Inventory

Finance

History

Knowledge,
Models

**Processing
& decision-making**
(Computational and
human)

Instructions

Information

Sensors
(Mechanical
and human)

Data

Actions

Actuators
(Mechanical
and human)

Figure 1: Communications flow in integrated manufacturing,
maintenance and control

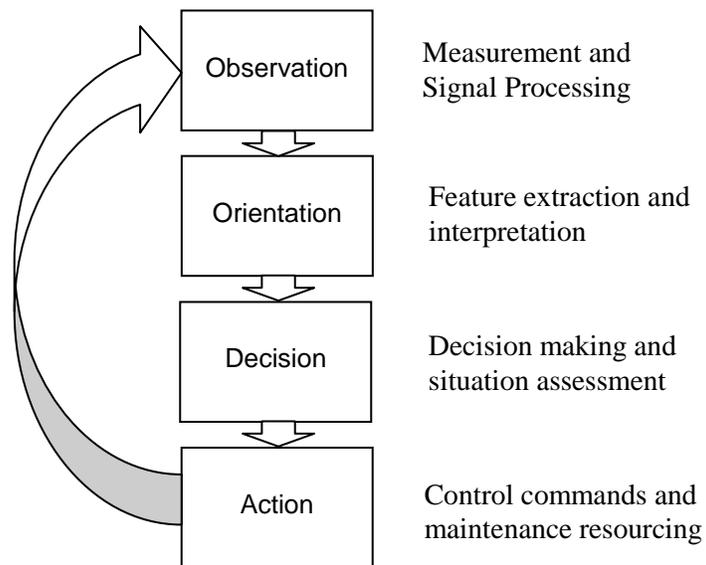|	
Observation	Measurement and Signal Processing
Orientation	Feature extraction and interpretation
Decision	Decision making and situation assessment
Action	Control commands and maintenance resourcing

Figure 2: The Boyd control loop adapted to monitoring and control
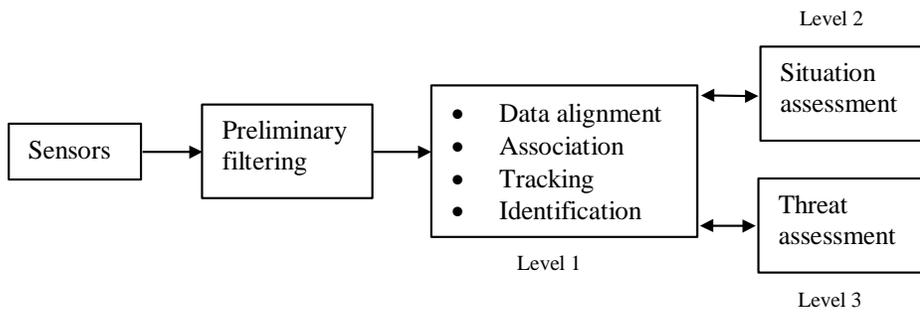*With acknowledgements to O'Brien and Bedworth*

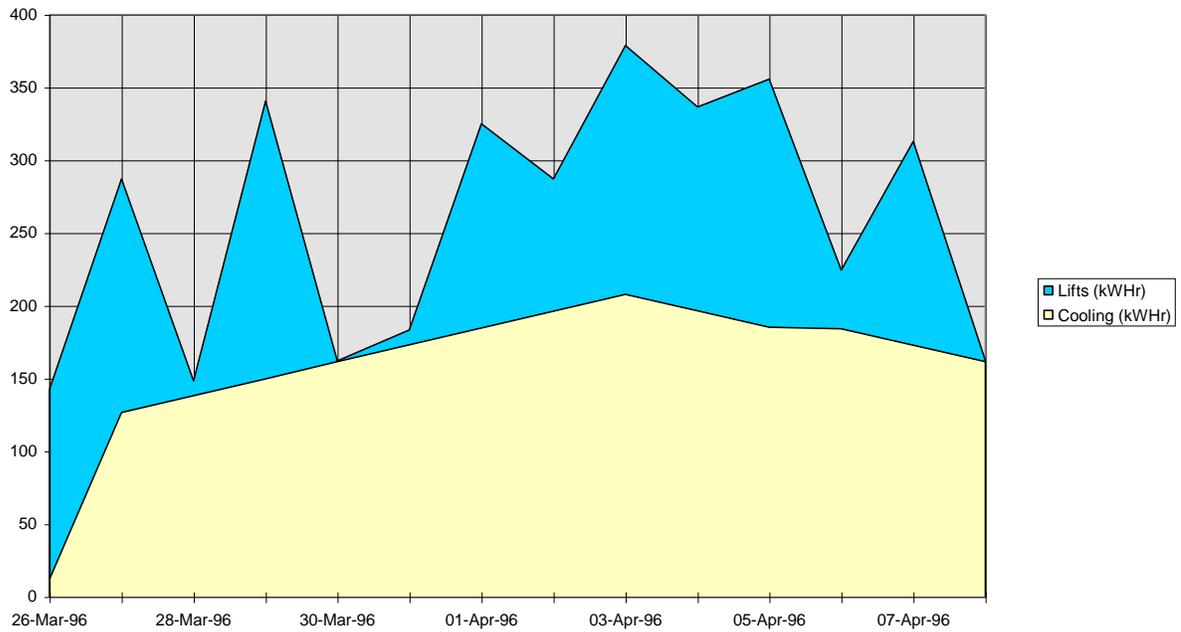**Figure 3**: The JDL model framework for data fusion

Figure 4: Electrical services consumption data in a large building complex, recorded by the BEMS and transferred to the FMS
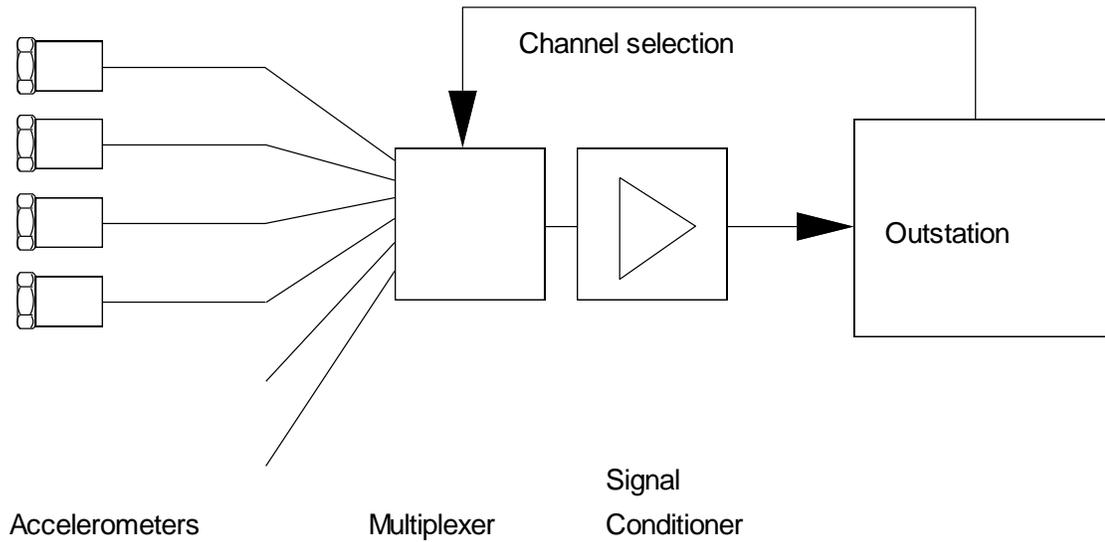
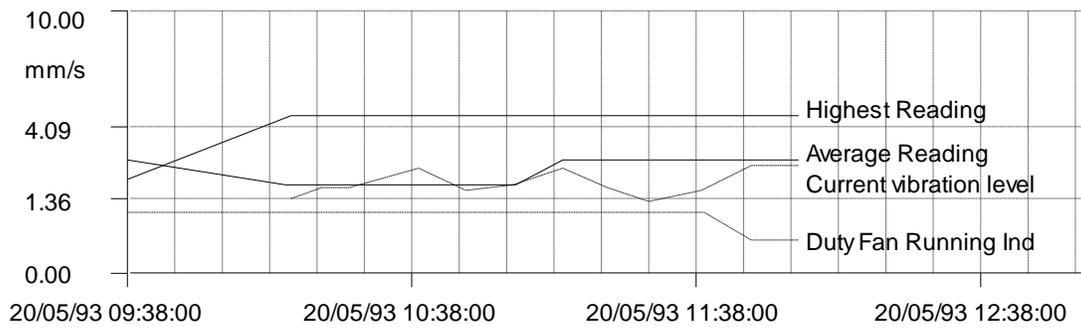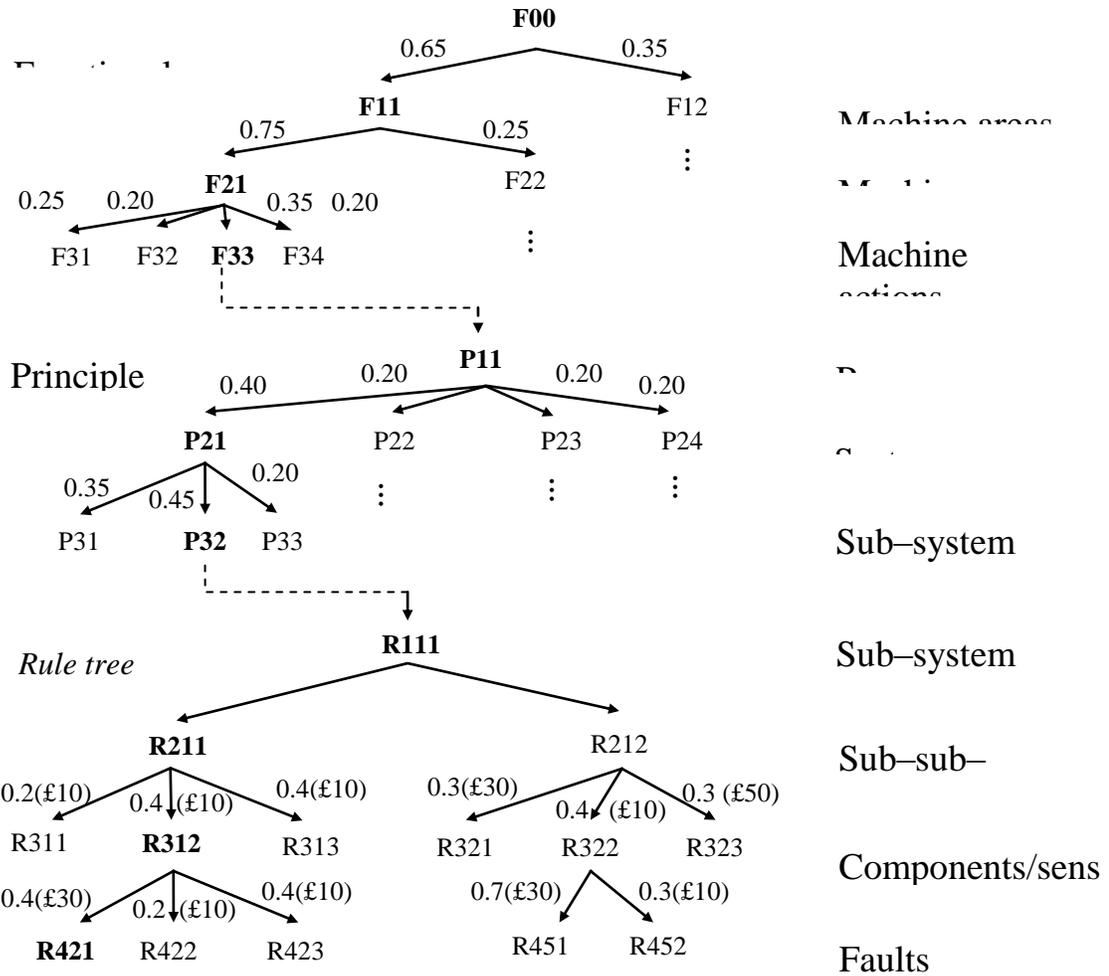**Figure 5a:** Multiplexed vibration inputs to a BEMS outstation

Figure 5b: Monitored data from the BEMS

F00
0.65   0.35

F11   F12
0.75   0.25

F21   F22
0.25   0.20   0.35   0.20

F31   F32   **F33**   F34

Functional   Machine areas

Machine

Machine
actions

Principle   P

0.40   0.20   **P11**   0.20   0.20   S

P21   P22   P23   P24
0.35   0.45   0.20

P31   **P32**   P33   Sub–system

Principle

Rule tree   **R111**   Sub–system

R211   R212   Sub–sub–
0.2(£10)   0.4(£10)   0.4(£10)   0.3(£30)   0.4(£10)   0.3 (£50)

R311   **R312**   R313   R321   R322   R323   Components/sens
0.4(£30)   0.2(£10)   0.4(£10)   0.7(£30)   0.3(£10)

R421   R422   R423   R451   R452   Faults

Functions
F00: FFS-1500-2 FMS
F11: Machine Tools
F12: AGV
F21: PFZ1500 FMC
F22: KBNG85 MC
F31: Tool Change
F32: Tool-head Change
F33: Machining Process
F34: Hydraulic Drive

Principles
P11: Machining Process
P21: Spindle
P22: X-axis
P23: Y-axis
P24: Z-axis
P31: Spindle Feed
P32: Spindle Motor
P33: Spindle Transmission

Rules
R111:   Spindle Motor
R211:   Motor Drive
R212:   Control Circuit
R311:   Mechanical Parts
R312:   Motor Temperature
R313:   Motor Connection
R321:   Circuit Connection
R322:   Power Connection
R323:   Control Amplifier
R421:   Tool Edge
R422:   Cooling System
R423:   Feed Load
R451:   Fuse
R452:   Power Switch

Figure 6. A diagnostic reasoning procedure for a machine tool [35]
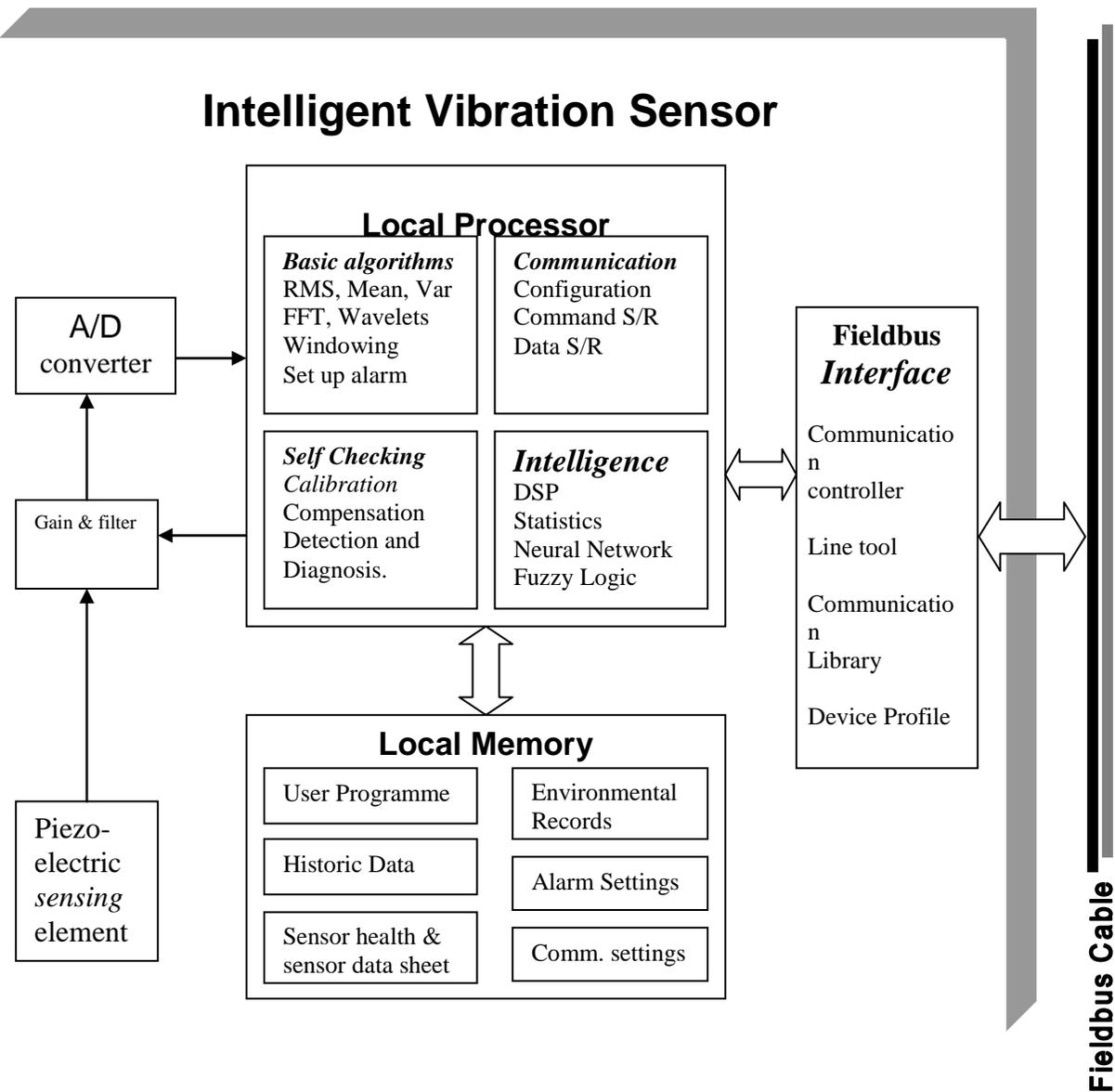
Intelligent Vibration Sensor

Local Processor

Basic algorithms
RMS, Mean, Var
FFT, Wavelets
Windowing
Set up alarm

Communication
Configuration
Command S/R
Data S/R

Self Checking
Calibration
Compensation
Detection and
Diagnosis.

Intelligence
DSP
Statistics
Neural Network
Fuzzy Logic

A/D converter

Gain & filter

Piezo-electric *sensing* element

Local Memory

User Programme

Historic Data

Sensor health & sensor data sheet

Environmental Records

Alarm Settings

Comm. settings

Fieldbus *Interface*

Communication controller

Line tool

Communication Library

Device Profile

Fieldbus Cable

Figure 7: Schematic of the demonstrator Fieldbus–based smart sensor
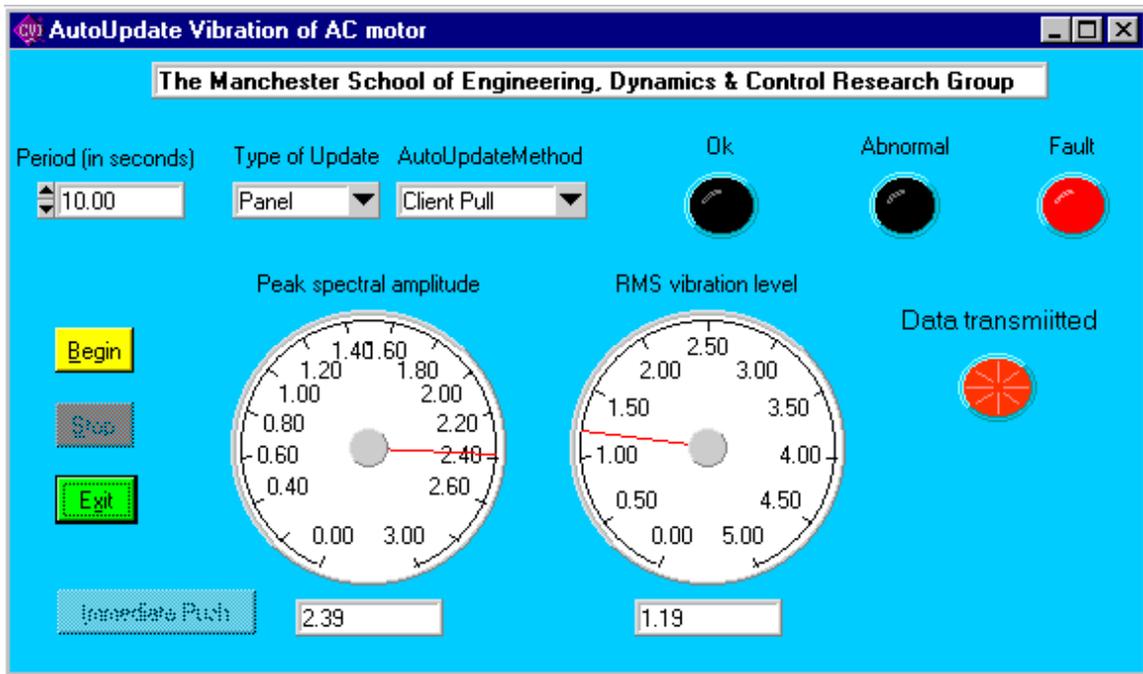
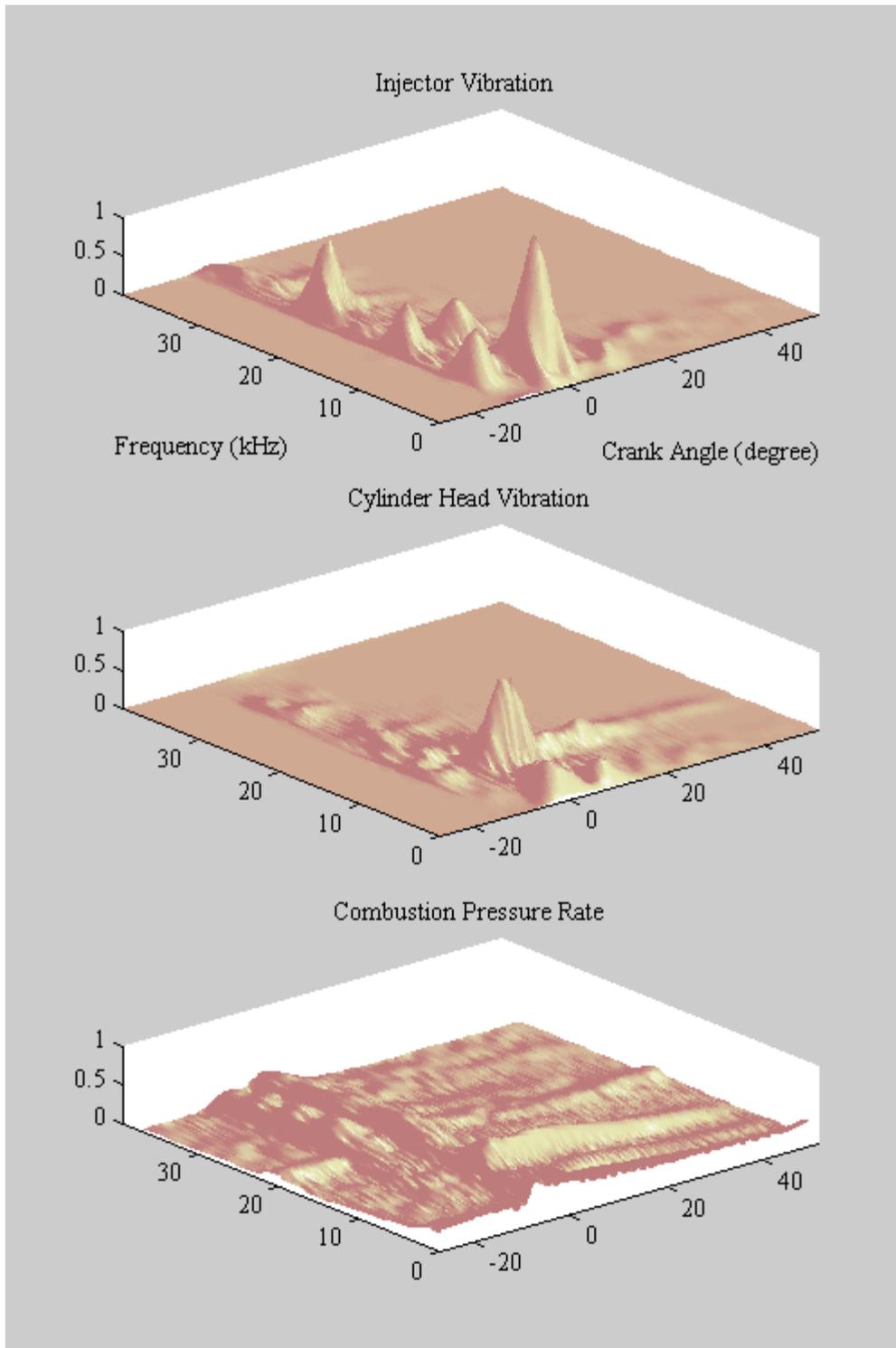**Figure 8:** Web page output from the demonstrator smart sensor

Figure 9: Characterisation of a diesel fuel injector from vibration and cylinder
pressure, displayed in time–frequency plots
Engine FSD425 operating at 59.7Nm and 2043 rev./min.