Systems integration in maintenance engineering

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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 bidirectional 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 organization 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 globalized 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.

Keywords: maintenance engineering, integration, condition monitoring, control, communications

NOTATION

Abbreviations

BEMS	building energy management system
CBM	condition-based maintenance
CENELEC	European Committee for Electrotechnical Standardization
CM	condition monitoring
CMMS	computerized maintenance management system
EAM	enterprise asset management
EN	Euro Norm
FFT	fast Fourier transform
FMS	facilities management system
HUMS	helicopter usage and monitoring system
IDEF	integrated computer-aided manufacturing definition
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
IT	information technology
JDL	Joint Directors of Laboratories (US military)
MIMOSA	Machinery Information Management Open Systems Alliance
MIS	management information system
OODA	observation, orientation, decision and action
OPC	Object Linking and Embedding 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

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1 INTRODUCTION

Integration is a holistic approach: it sets objectives for a system as a whole, and hence specifications. The systems approach determines inputs and outputs and, in this context, maintenance engineering aims to optimize 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 organize resources against scheduled and unscheduled tasks in many different ways, all of which are effective in their own way:

(a) simple communications, by word of mouth or on paper;
(b) time-based planning on cards or wall charts;
(c) computerized inventory, spares and job planning.

These methods have limitations in speed, automation and optimization. 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, localized information storage and processing methods make it difficult to link across to wider systems.

The enlightened organization recognizes 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 organization 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 organization to work to the same objectives. The technological advances can realize their full potential only in this framework.

It is estimated that the penetration of condition monitoring (CM) is only 10–20 per cent of its potential. This represents a loss of up to £1.6 billion 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, including the following:

(a) open global electronic information systems;
(b) adaptive shared communications media;
(c) smart sensors;
(d) 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 optimizes 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 computerized maintenance management systems (CMMSs) aims to prolong and enhance equipment and tool life, and to reduce maintenance costs.

1.2 The technology of integration

Several enabling technologies have penetrated the maintenance sector. Hand-held personal computers (PCs) 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 importance in many industrial sectors:

(a) *electricity distribution*: integration of control, quality, scheduling and maintenance over supervisory control and data acquisition (SCADA) in high- and medium-voltage networks [**12**]; remote on-line monitoring of electricity substations [**13**];
(b) *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**];

(c) *power generation*: integration of operations, engineering and maintenance by providing data and software applications in a common environment [**16**];

(d) *military applications*: very high levels of integration in weapons support, integrating display, modular instrumentation, information bank and diagnostics [**17**]; helicopter usage monitoring systems (HUMS) that are well advanced [**18**];

(e) *rail*: integration of wayside monitoring devices with maintenance systems to detect faults in freight cars and to reduce manual inspection requirements by US operator Conrail [**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 globalized 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 there are business-oriented systems. Maintenance management sits below the business systems and in a traditional organization sits alongside production. In an integrated business, maintenance is part of the production organization. CM 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; therefore the life cycle of those assets, and the cost associated with them, is fundamental to the success of the business.

Before a maintenance plan is even considered, several important decisions have usually been made:

(a) the purpose of the business associated with the assets;
(b) the risk associated with investing in the assets;
(c) 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 (CBM) 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 computerized:

1. *Plant inventory/asset register*. An identification scheme is essential to the system.
2. *Job catalogue*. Time-based PPM tasks are stored as a 'tool kit' which is applied to the plant.

3. *Work planning*. Scheduling jobs and matching required skills to resources are needed.
4. *Stores*. A catalogue of spare parts in stock, containing ordering information is required; over 10 000 items is common.
5. *Report generation*. This is important for day-to-day running tasks and performance summaries.
6. *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

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. 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:

1. Advanced warning of failure is given, so that repairs can be planned out of production time.
2. Inconvenient breakdowns and expensive consequential damage are minimized.
3. The failure rate is reduced, thus improving plant availability and reliability.
4. A reduced spares inventory can be carried.
5. 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 the following:

1. Power stations monitor vibration, thermal emissions and lubricants using on- and off-line techniques. Steam turbines, for example, contain large masses rotating at a 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.
2. 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 are transferred to a host computer at the end of the data collection tour.
3. 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 are 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:

1. 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.
2. The temperature of a soldering vessel is required to be kept within a tight band, by continuous variation in 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 realize complex control algorithms which are dependent 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 in Fig. 1:

(a) their hierarchical structures, which pass messages and requests down to the plant and return signals and information to higher levels of supervision;
(b) 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 feedback 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.

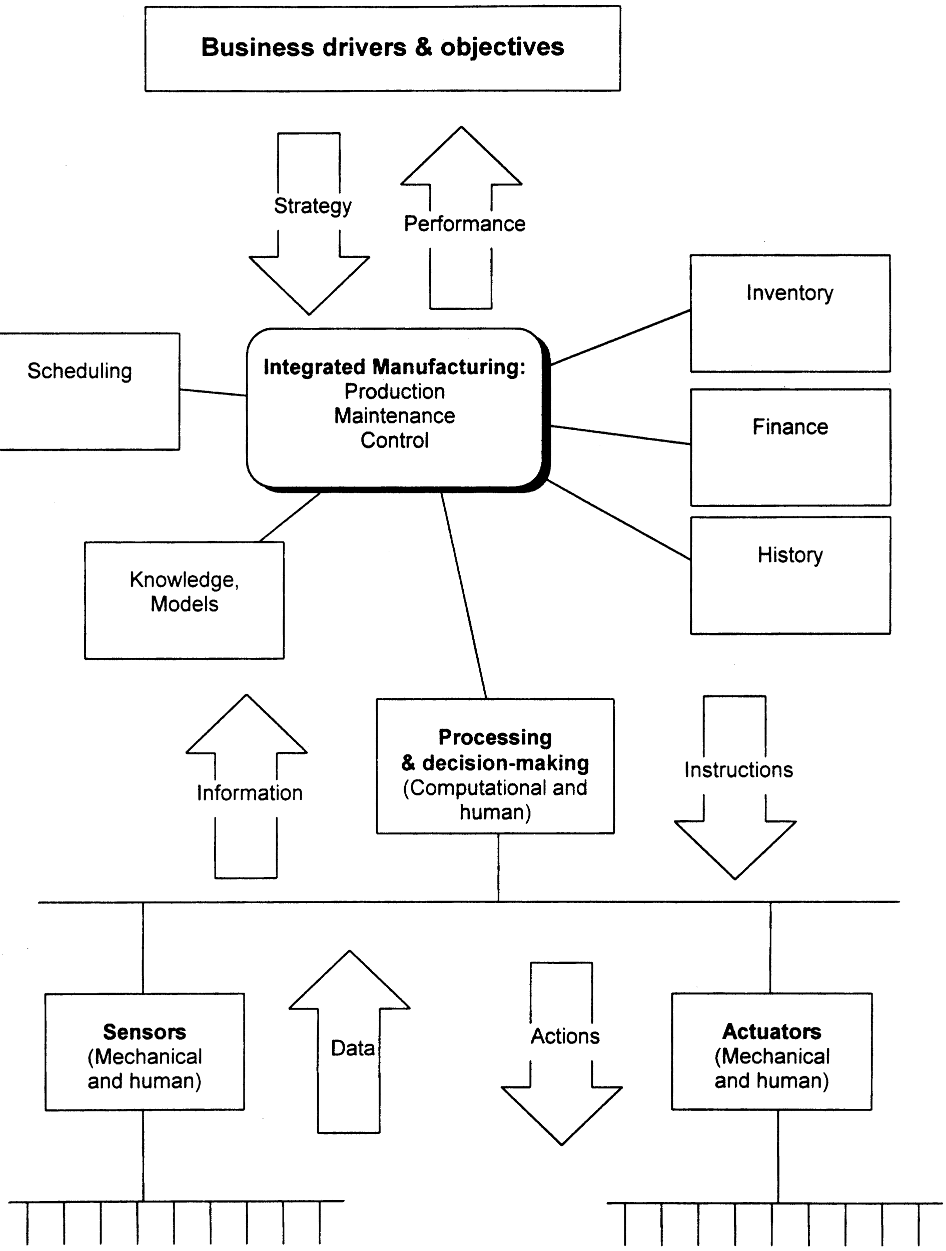


Fig. 1 Communications flow in integrated manufacturing, maintenance and control

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: CONCEPTUALIZATION 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 information technology (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 has been impossible to realize 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:

(a) avoidance of duplication, i.e. shared information and reduced effort;
(b) greater robustness and reliability;
(c) tighter loops in the broad sense of control, i.e. less effort for the same gain or more output for the same input;
(d) a 'total' approach improves many human and management issues.

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

(a) field devices (sensors);
(b) final control elements (actuators);
(c) process control units;
(d) CM systems;
(e) 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 CM system will perform its conventional tasks (e.g. data trending and abnormality detection) but it may also utilize 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, CM and manufacturing systems. The cost of the microelectronic components continues to fall, and digital electronics are 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 programmable logic controllers (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 standardize 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 (such as 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:

1. *Standardization*. There is modularization of hardware and software, and *de facto* commonality.
2. *Human issues*. The technology of system design and realization is becoming more widely accepted and skills are being developed.
3. *Cost*. There is a 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 to plan solutions [**23**]. For example, in computerized information systems, structured methods for design use modelling, definition and analysis techniques, such as structured systems and design methodology (SSADM) or integrated computer-aided manufacturing definition (IDEF). The following characteristics are common in methods such as SSADM and IDEF [**24**]:

1. A project is structured into small well-defined activities; the sequence and interaction of the activities is specified.
2. 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, formalized methods are being created which are partly embodied in RCM [**26**]. These procedures aid the decisions in selection and design of a condition-based maintenance programme by using a consistent scheme which (a) defines the known information in a criticality analysis and a maintenance audit, i.e. defines the problem, (b) 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, and (c) 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 Fig. 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

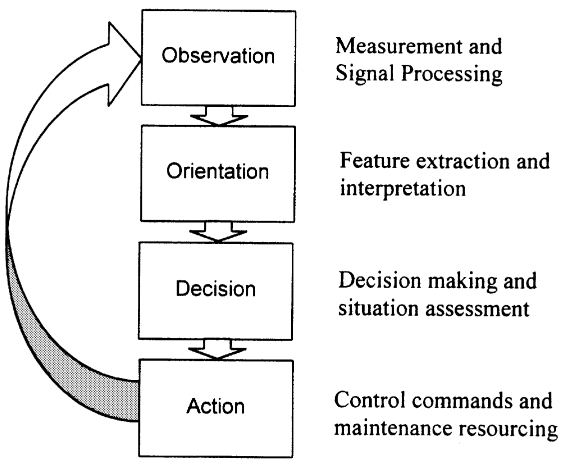


Fig. 2 The Boyd control loop adapted to monitoring and control

microcomputers for monitoring purposes. Unlike computer network protocols (e.g. Ethernet), Fieldbuses are optimized 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 4–20 mA analogue network system. The advantages include the following:

1. Digital signals are more robust in the presence of noise.
2. Cabling costs are substantially reduced because all devices are linked up on the same cable.
3. Modularity allows reconfiguration and upgrading.
4. There is 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 not only that the Fieldbus prevents disturbance of time-critical traffic by messages, but also 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 are already passing without any disturbance to the network traffic. Therefore, for example, it is simple to add a SCADA system or gateway to 'piggy-back' on a PLC–remote input–output network without changing the PLC program 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:

(a) Foundation Fieldbus (USA: the major distributed control system manufacturers);
(b) Profibus (Germany: Siemens);
(c) WorldFIP (France: Alstom, Cegelec, Groupe Schneider/Telemecanique).

An International Fieldbus, International Electrotechnical Commission (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 and 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 5–10 years.

There are many other proprietary protocols which claim to be a Fieldbus. There is also a European Standard, Euro Norm (EN) 50170, issued by the European Committee for Electrotechnical Standardization (CENELEC), which includes WorldFIP, Profibus and P-Net as three solutions for general-purpose field communications. The Fieldbus standardization process has recognized the need to support background messages for configuration, diagnostics and CM. This is reflected strongly in the IEC Standard and in WorldFIP.

3.4.2 Other emergent standards

While Fieldbus is creating a sea change in control architectures, several emergent standards are influencing the use of data at a higher level in maintenance and control. Among these, Machinery Information Management Open Systems Alliance (MIMOSA), Standard for the Exchange of Product Model Data (STEP) and Object Linking and Embedding for Process Control (OPC) have significant impact.

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**].

STEP is the familiar name for ISO 10303 (International Organization for Standardization) [**30**]. STEP was 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, which offers huge advantages for the manufacturing sector and hence has many parallels with maintenance and 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:

(a) increased processing power;
(b) distributed processing, which localizes intelligence near to (or within) the sensor;
(c) 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 maximizing the useful information content, for improved reliability or discriminant capability, while minimizing the quantity of data ultimately retained [**32**]. The sensor and signal processing communities have been using fusion to synthesize the results of two or more sensors for some years. This simple step recognizes the limitations of a single sensor but exploits the capability of another similar or dissimilar sensor to calibrate, to 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 with the Boyd loop and is embodied in the Joint Directors of Laboratories (JDL) model as shown in Fig. 3 [**33**]. In real problems, it is not always necessary to apply all the stages:

1. *Pre-processing*, i.e. reduction in the quantity of data while 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.
2. *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.
3. *Post-processing*, combining the mathematical data with knowledge and decision making. Techniques could be classified as knowledge-based, cognitive-based, heuristic and statistical.

Classical CM 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 multi-variate 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:

1. *Sampling*. This is traditionally controlled by the host;

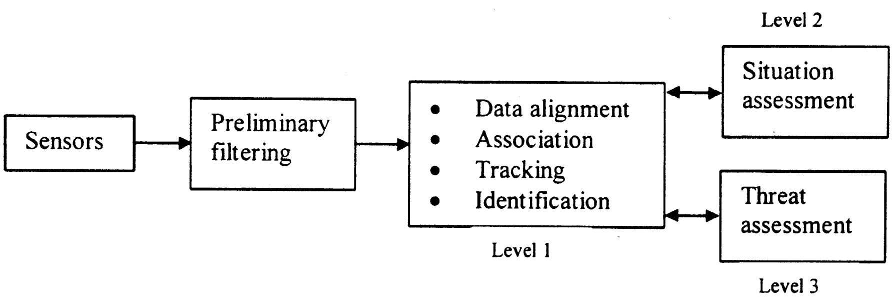


Fig. 3 The JDL model framework for data fusion

the on-board algorithm of a smart sensor can dictate when and how the signal is sampled.
2. *Processing and memory*. The computing power to perform signal processing has traditionally been expensive, leading to high-bandwidth data acquisition systems and centralized 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.
3. *Communications interfaces*. Integrated 4–20 mA interfaces are commonplace, but the smart sensor can also include and control a wireless transceiver, modem, Ethernet adapter, Fieldbus node or internet host. Bidirectional communication is necessary to allow the host to send instructions, and for the sensor to return status information or data.
4. *Decision making*. The on-board algorithm can control any function, e.g. whether or not to transmit data, and how much.
5. *Calibration*. Local measurement of conditions can be used for correction and compensation prior to data transmission.
6. *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 CM 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 prioritization 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 CM. 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 also permits optimization 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. Reprogrammable 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 consist of 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:

(a) management systems;
(b) decision-level fusion;
(c) CM over a Fieldbus network;
(d) advanced signal processing algorithms for feature extraction on a smart sensor.

4.1 Integration of management information systems

Many MISs 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 the following:

(a) resources, i.e. plant and spares inventory, personnel, skills and tools;
(b) suppliers and customers, cost estimating, purchasing and billing;
(c) planning and scheduling, activities and installations;
(d) reporting and graphical output;
(e) 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 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:

1. All systems require a plant inventory structure for identification.
2. The BEMS can generate valuable utilization and costing information for the FMS.
3. The FMS may contain scheduling information which will be used to program the BEMS.
4. 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, Fig. 4 shows a sample of the services consumption data in a large building complex. The BEMS was programmed to summarize consumption of electricity, gas and water on a daily basis. The information was passed through a spreadsheet, which allowed live updating through the dynamic data exchange, 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. 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 diagram for interfacing vibration data collection to the BEMS and Fig. 5b shows a typical report.

4.2 Knowledge-based decision fusion

In complex systems, decisions are made on the basis of measured parameters, but these are related to knowledge about the way that the systems operate. In manufacturing systems, for example, operational faults account for about 70 per cent 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 PLC. With these models working together, the

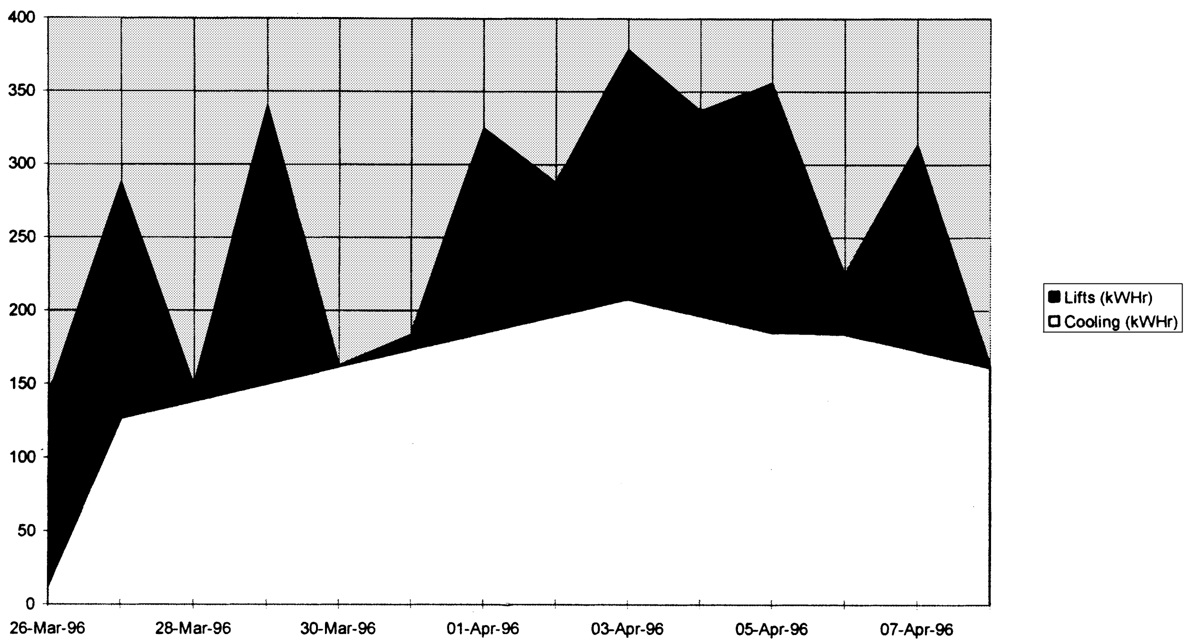


Fig. 4 Electrical services consumption data in a large building complex, recorded by the BEMS and transferred to the FMS

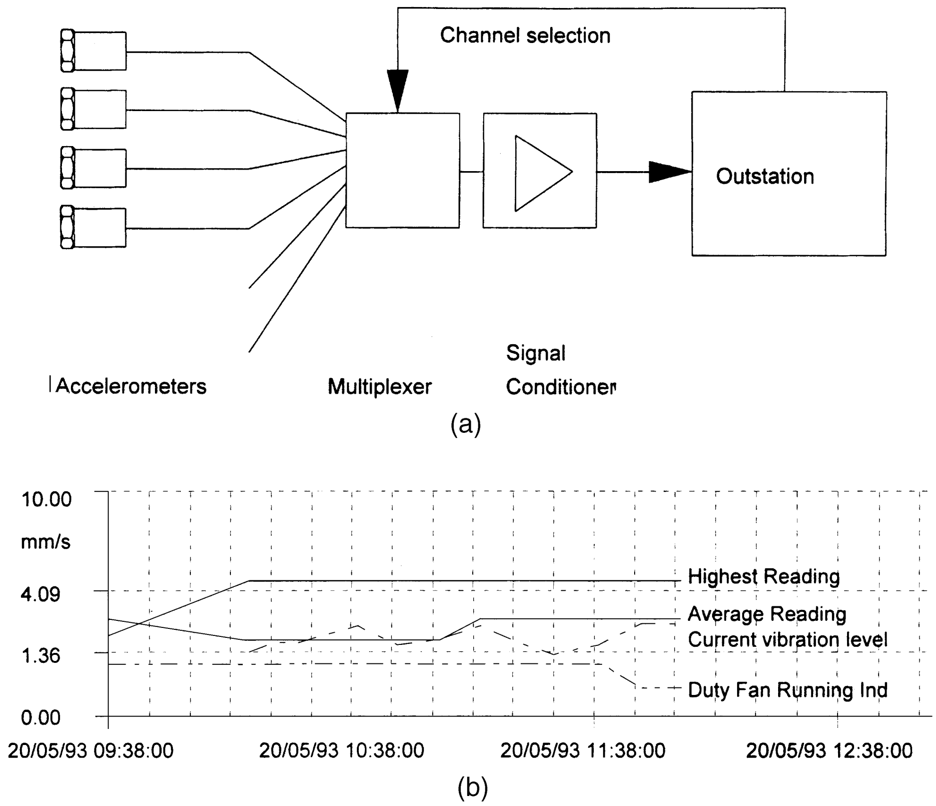


Fig. 5 (a) Multiplexed vibration inputs to a BEMS outstation. (b) Monitored data from the BEMS

operational faults of a manufacturing system can be diagnosed completely. The models have been successfully applied to a flexible manufacturing system controlled by a PLC and have achieved good results [**35**].

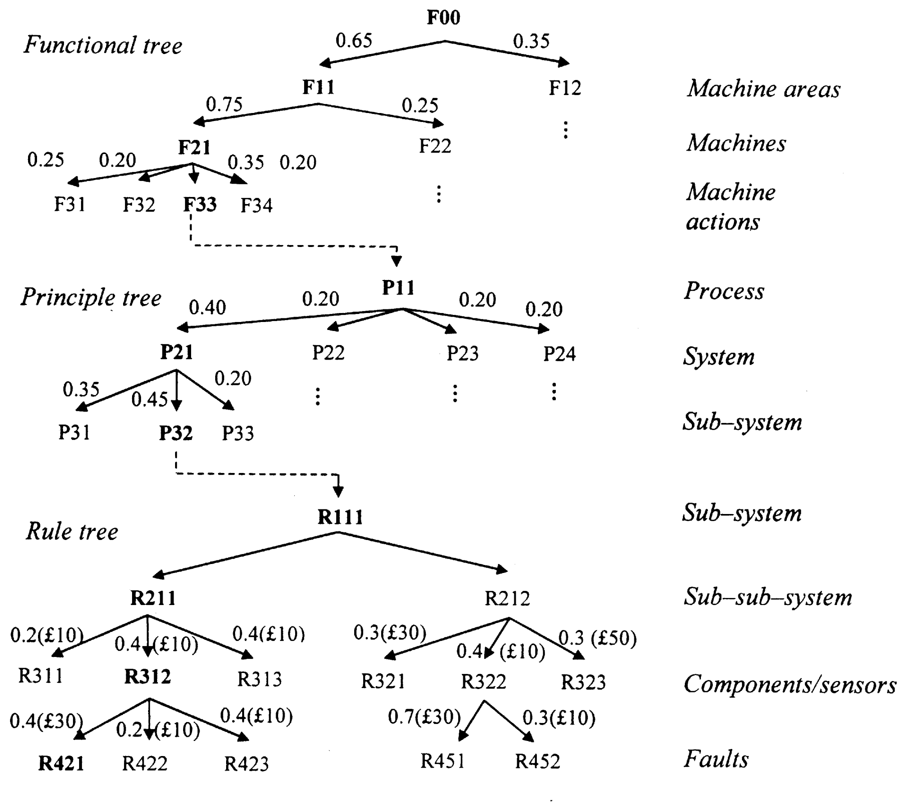
The model combines knowledge about the intended operating procedure with measured inputs from the normal automation sensors. The stage of the programme indicates the broad area of the fault, and the status of the measured inputs localizes the solution further. In the example shown in Fig. 6, a system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

1. In the functional tree, it is first established that the flexible manufacturing system 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).
2. According to the principles of operation of the machining process (P11), the highest probability lies in a spindle failure (P21: 0.4) and, in this case, the most likely fault is the spindle motor (P32: 0.45).
3. 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 faults 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 CM. A PC was programmed to act as a combined bus arbitrator and CM controller, and another as a remote node and intelligent sensor. 50 per cent of the Fieldbus bandwidth was deliberately occupied by the continuous transmission of simulated time critical control variables. On the Fieldbus between the two PCs a field tap was provided to permit a third PC to access the Fieldbus and to transmit the data to an Ethernet link to an Internet server. The server provided worldwide real-time access to the CM 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 diagram of the demonstrator system, and Fig. 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



Functions	Principles	Rules	
F00: FFS-1500-2 FMS	P11: Machining Process	R111:	Spindle Motor
F11: Machine Tools	P21: Spindle	R211:	Motor Drive
F12: AGV	P22: X-axis	R212:	Control Circuit
F21: PFZ1500 FMC	P23: Y-axis	R311:	Mechanical Parts
F22: KBNG85 MC	P24: Z-axis	R312:	Motor Temperature
F31: Tool Change	P31: Spindle Feed	R313:	Motor Connection
F32: Tool-head Change	P32: Spindle Motor	R321:	Circuit Connection
F33: Machining Process	P33: Spindle Transmission	R322:	Power Connection
F34: Hydraulic Drive		R323:	Control Amplifier
		R421:	Tool Edge
		R422:	Cooling System
		R423:	Feed Load
		R451:	Fuse
		R452:	Power Switch

Fig. 6 A diagnostic reasoning procedure for a machine tool [**35**]

necessary for consumption by the MISs that would in reality be present on the same network. Specifically, the monitoring strategy was defined as follows:

1. Routinely request a condition status (i.e. a green, amber or red traffic light) from the intelligent sensor.
2. If status is green, record status and time stamp; then wait 60 s until next status indicator is required.
3. If status is amber, record status and time stamp; then request and record data summary; then reduce subsequent monitoring interval to 15 s.
4. If status is red, record status and time stamp; then request and record full data transmission; then reduce subsequent monitoring interval to 15 s and issue a warning message on to the network for consumption by the MISs.

There are numerous ways in which this monitoring strategy could be changed or refined. The system demonstrated 'on-request' communication of CM 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:

(a) sensing, filtering and amplification of vibration acceleration data;
(b) sampling and digitization;

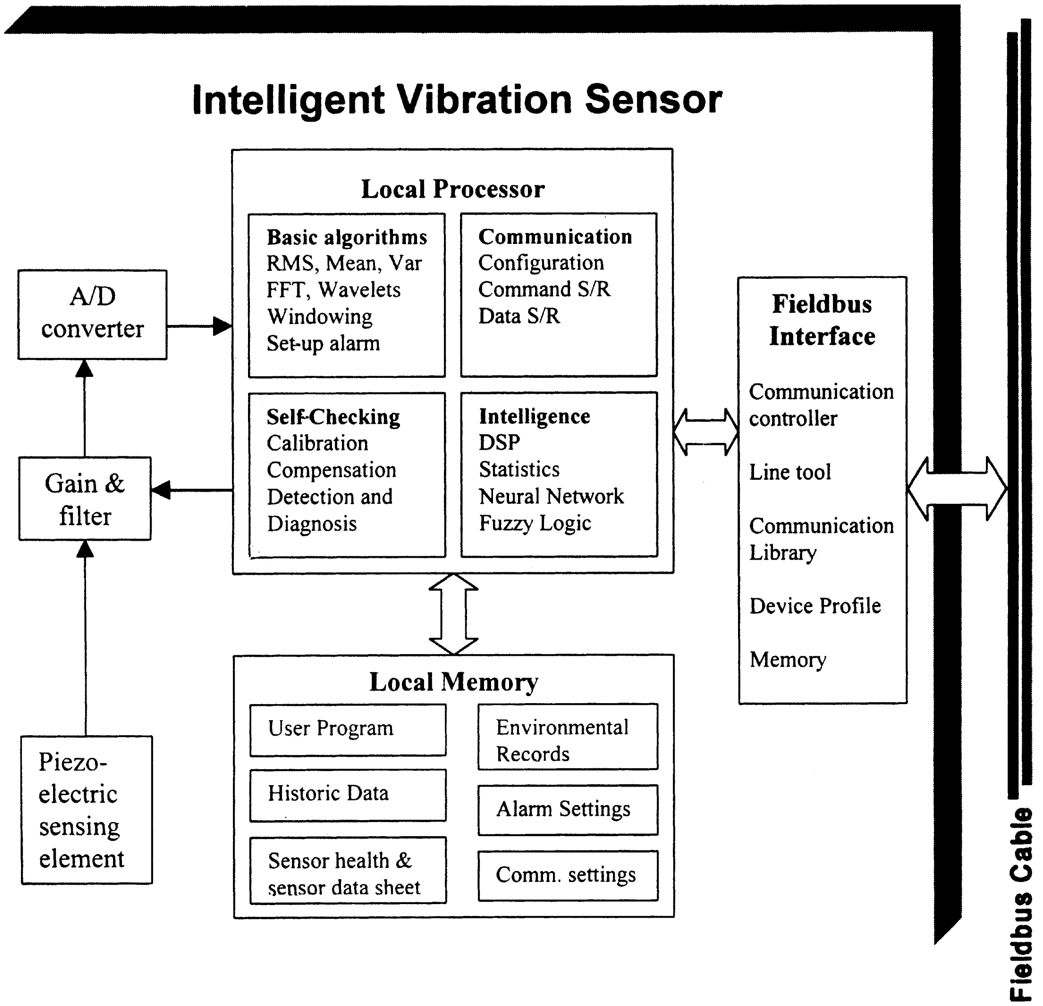


Fig. 7 Schematic diagram of the demonstrator Fieldbus-based smart sensor (A/D, analogue-to-digital; DSP, distributed system program)

(c) calculation of the r.m.s. level and frequency spectrum [fast Fourier transform (FFT)];
(d) comparison of processed output with thresholds;
(e) determination of the current status;
(f) on request from the CM 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 CM 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 that 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 Fig. 9 demonstrates the characterization 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.

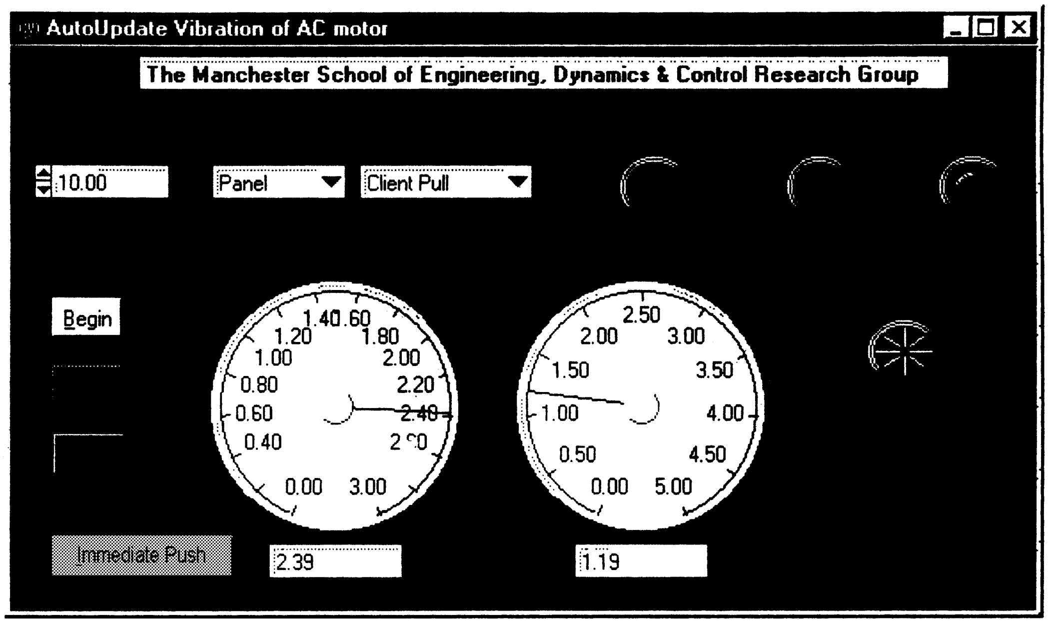


Fig. 8 Web page output from the demonstrator smart sensor

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 realization 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 life-cycle 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 utilization 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 CM.

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 centralized 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.

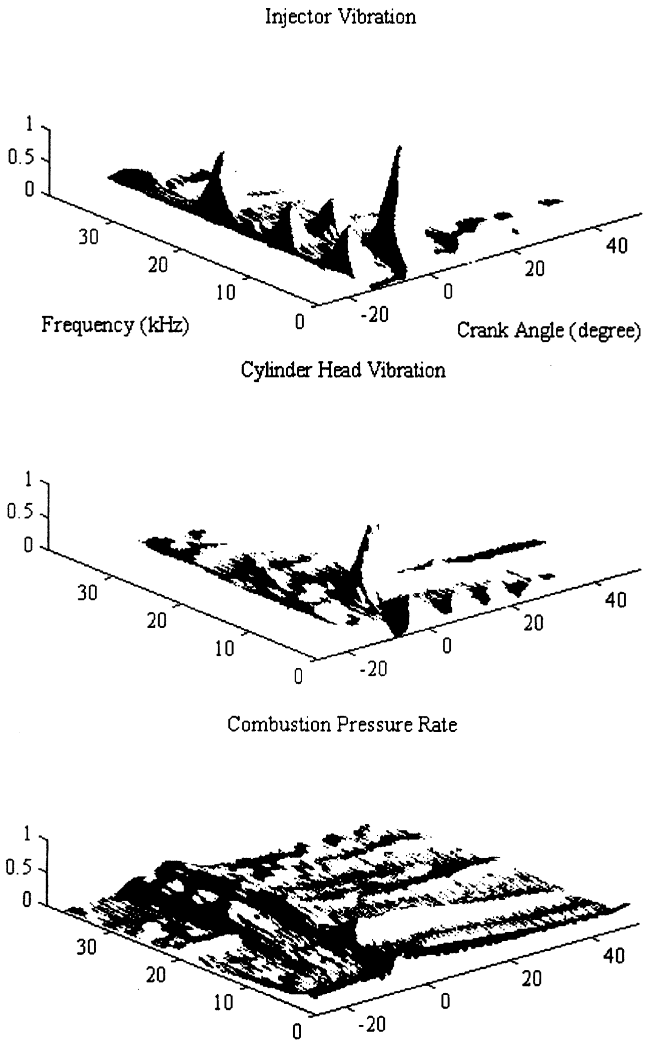


Fig. 9 Characterization of a diesel fuel injector from vibration and cylinder pressure, displayed in time–frequency plots. The engine FSD425 was operating at 59.7 N m and 2043 r/min

5.6 Future directions

Examples of the levels of integration have been shown which demonstrate performance benefits, on both a technical and a business level. Considerable work remains to be done to realize 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 the potential benefits. Sustained collaboration and standardization will be essential.

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