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Diagnostics of Mobile Machinery: Future Trends

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Summary

In this report various future trends are listed for mobile machinery diagnostics. Standards, legislation, sensors, vehicle networks, data-analysis and prognostics are discussed. Mobile machinery diagnostics are studied from two points of view: process industry condition monitoring and automotive vehicle diagnostics. Some standards for these industries are listed. Sensor discussion is mainly from an automotive point of view and vehicle networks are targeted towards wireless communication. The data-analysis part includes basics of neural networks, fuzzy systems and genetic algorithms. Bayesian networks are also covered into some depth. In the end an example of modern vehicle diagnostic system is presented.

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Foreword

This report has been prepared for the purposes of the project Monitoring and diagnostics - Lifetime management of mobile machinery.

Espoo, October 31st, 2002

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1 Introduction

Diagnostics is defined as the "detection of a faulty component and malfunctioning element causing a control system failure" in the ISO and SAE standards and in the Japanese JASO standard [Mogi, 2000]. In the passenger car industry various diagnostic methods for vehicles have been developed for monitoring needs. Commercially available diagnostic systems are of two types: on-board (the diagnostic function control and components are mounted on the electronic controller of the car) and off-board (using external devices). Passenger car industry volumes have diminished the price of sensors, bus solutions and microprocessors for on-board technology. Thus it makes sense to add diagnostic systems to less volume-mobile machinery. Because production loss can be extremely high when a machine breaks down, using more expensive methods and equipment from the process industry is justifiable in preventing it.

It has been estimated that in the near future machinery manufacturers will sell capacity rather than machinery to the end user. This requires a fast response of the manufacturer to possible faults, placing emphasis on machinery diagnostics and continuous monitoring. Mobile targets require wireless communication, and the amount of information sent through wireless channels should be small. From here there are two ways to proceed: on-board diagnostics or telediagnostics. The choice is based on factors such as the amount of equipment requiring diagnostics, the amount of data to be transferred, and the business idea of the company. The most economical way would be to develop a self-diagnostic ability for machinery.

If capacity selling is more the long-term future, maintenance research is an important field in the short term also. In the automotive section, competition has cut profits in car sales. Profit increases come mainly from parts sales and other services. This may also be the future of mobile machinery as investors demand higher and higher profits. Service will also balance the profits in fluctuating machinery markets.

2 Standards and Legislation in Diagnostics

The development of diagnostic standards is driven by the automotive industry. In mobile machinery, safety is more standardised [ISO, 2002]. Legislation in off-road vehicles focuses mainly on combustion engine emission [NSSN, 2002a]. Mobile machinery is approaching the automotive level in diagnostic standards and legislation; therefore it makes sense to approach the future from an automotive point of view. Sometimes mobile machinery may be more a process plant than a road vehicle, like large mobile mineral crushing and screening equipment which includes hydraulics and process control as well. Therefore it is also appropriate to study possibilities of using process standards in mobile machinery.

2.1 The Automotive Industry

Until recently, most vehicle manufacturers had their own communications protocols for data transfer through diagnostic connectors. They also had their own plug-and-socket devices and company-specific testers. This enabled car manufacturers to control the company's diagnostic data and to design the diagnostic equipment to be company-specific [Bremer, 2000].

This situation has changed radically due to the necessity for air-pollution control. Legislation governing maximum exhaust-gas and particulate concentrations has become stricter. Simultaneously rules have been defined for standardisation of procedures and testers. These developments originated in the United States. The procedures for the measurement of exhaust-gas-relevant data have now become familiar worldwide through the term OBD (On-Board Diagnostics). OBD and now EOBD (European On-Board Diagnostics) have become synonymous to worldwide standardisation of methods and procedures for the transfer of diagnostic data with specified diagnostic services from the vehicle through a standardised plug- and -socket connection to the external standardised testers (scan tools), which must comply with a wide range of specified technical requirements [Bremer, 2000].

National and international standardisation authorities drew up OBD standards to govern all relevant sectors (Table 1 and Table 2). In their legislation, these lawmakers then defined those standards as binding. Here also, developments began in the United States, where the Society of Automotive Engineers (SAE), together with the California Air Resource Board (CARB) and the Environmental Protection Agency (EPA), drew up a comprehensive series of binding standards [Bremer, 2000].

In Europe and Japan, legislation is aimed at internationally harmonised exhaust-gas control standards, and at the beginning of the 1990s the International Organisation for Standardisation (ISO) began its own standardisation work. Cooperation between SAE and JSAE (SAE in Japan) has led to the development of standards that are identical worldwide and that differ only to the extent dictated by national legislation [Bremer, 2000].

The following equipment and procedures are standardised and stipulated by international agreements on standardisation: the diagnostic connector, its mechanical functioning and its pin assignments; the protocols to be used; the diagnosis routines; the trouble codes; the technical requirements for the diagnostic unit; and the minimum stipulations for ensuring reliable, manipulation-proof data access. A listing of the SAE and ISO standards that have been drawn up for the passenger-car sector and that are stipulated by legislation is presented in Table 1 [Bremer, 1999].

Table 1. List of corresponding ISO and SAE documents (not including the standards covering the stipulated data protocols)[Bremer, 1999].

SAE Document	**ISO Document**	**Title of ISO Document**
J 1930	15031-2	Terms, definitions, abbreviations, and acronyms
J 1962	15031-3	Diagnostic connector and related electrical circuits: Specifications and use
J 1978	15031-4	External test equipment
J 1979	15031-5	Emission-related diagnostic services
J 2012	15031-6	Diagnostic trouble-code definition
J 2186	15031-7	Data-link security

Due to the harmonisation process between the ISO and SAE standardisation committees, it was possible to make the technical content of the standards in Table 1 [Bremer, 1999] practically identical. Document numbers are equally valid for one and the same technical content. As a result, SAE will in the future take this into account by giving its documents a two-part number. For example, for the diagnostic connector, the number will be SAE J1962/IS0 15031-3. This two-part numbering system will lead to CARB and EPA including the relevant references in their regulations, whereas the European legislation (European Union, EU) will take into account only the international standards (ISO documents). For the data protocols, four different possibilities have been left open by the lawmakers, as shown in Table 2 [Bremer, 1999].

Table 2. Standards for data communications protocols [Bremer, 1999].

SAE Document	**ISO Document**	**Title of ISO Document**
	9141-2	CARB requirements for the interchange of digital information
J 1850	11519-4	Class B Data Communication Network Interface
	14230-4	Keyword Protocol 2000 -Requirements for emissions-related systems
	15765-4	Diagnostics on CAN-Requirements for emissions-related systems

The technology of ISO 9141-2 has become technically outdated and has been applied only in a very few new vehicles. It can be expected that this protocol will be superseded by more modern solutions such as the diagnosis protocol with CAN, i.e. ISO 15765-4 [Bremer, 2000].

The first three protocols in Table 2 are listed in the American, European, and Japanese regulations. ISO 15765-4 was approved by European legislators as a further protocol on January 1st 2000 (coming into effect for the Euro III limits for passenger cars). CARB and EPA in the United States are to give their approval in early 2003. European legislation permits two different data transfer rates (250 kBaud or 500 kBaud), but only 500 kBaud is permitted in the United States [Bremer, 2000].

2.1.1 Heavy Duty Vehicles (HDV)

There have been no clear indications regarding which protocols, plug-in connections, trouble codes, and diagnostic services will be applied in the United States and Europe in the commercial-vehicle/truck sector. This cannot, however, be attributed to non-existing binding introduction deadlines. In Europe, the introduction of diagnostic legislation for HDVs is expected in 2005 (coming into effect for the Euro IV limits). The introduction of an OBD for HDVs in the United States should take place at about the same time [Bremer, 2000]. With mobile machinery in mind, the HDV section could be more interesting, if compared to passenger vehicle standards.

In the United States, CARB and EPA have already accepted a further protocol for light commercial vehicles: J 1939- 73, which was drawn up by the SAE Truck and Bus Committee. This protocol is based on the CAN bus as per ISO 11898. It is logical to expect that J 1939-73 will also be accepted as the protocol for HDVs [Bremer, 1999].

In Europe the tendency is emerging to use the ISO 15765 protocol as standard for both commercial vehicles and passenger cars. Agreements have already been reached ensuring full compatibility of this protocol with J 1939 networks. A connected diagnostic unit has no difficulty in determining from the message format (the identifier or the parameter group defined in the identifier) that the ensuing message is to be interpreted as a diagnosis message in accordance with ISO 15765 [Bremer, 2000].

Insofar as the diagnostic connector is concerned, discussions are still ongoing and no decision has been reached. In the United States the diagnostic connector for the commercial-vehicle sector has already been defined by J 1939-13. In Europe, however, efforts are still underway to apply the same connector for HDVs as has already proved viable in the passenger-car sector (ISO 15031-3/SAE J 1962; see Table 1). It is still not clear how the higher commercial-vehicle power supply voltage (24 V) prevailing in Europe can be applied to the connector without destroying the passenger-car diagnostic units in cases of false polarity or inexpert handling [Bremer, 2000].

Appendix 1 shows a search result for the term ’diagnostics’ from two web-based databases: A National Resource for Global Standards (NSSN) and WebPages of the Society of Automotive Engineering. Other standards also emerge in addition to those mentioned. [NSSN, 2002b; SAE, 2002]

2.1.2 Future Prospects

Until now, the definition of OBD in legislation has been restricted to the specific requirements for exhaust-gas relevant diagnostics. In other diagnostics the vehicle manufacturers are still free to use company-specific protocols and test equipment. This means that other interested groups such as repair workshops, technical monitoring institutes for periodical technical roadworthiness tests, or road-repair organisations have no access to such diagnostic data. That is, these groups have no means, for example, to carry out rapid diagnosis of a broken vehicle [Bremer, 2000].

Legislation is becoming more concerned with including safety-relevant equipment or bodywork components in an OBD. Since all of the technical items have been agreed upon (i.e. the diagnostic connector, the diagnostic-services format, the protocols, and the test-equipment stipulations), the remaining task is to find agreement on the standardisation of suitable messages and trouble codes [Bremer, 2000].

Authorities in both Europe and the United States require vehicle manufacturers to make the information they provide to their franchised dealers freely available. It has been suggested to provide this information in a common format defined by SAE J2008. The same requirement is being considered by the European Commission. In 1999 the EPA published a "Draft Proposal of Intended Rule Making," which requires manufacturers to make repair information available only through the Internet. It does not require a specific format for that information. Recent proposals would add a requirement for meta-data to tag the repair information, in order to facilitate fast and accurate searches. Without a standardised format, full-context keyword searches on the Internet would certainly yield multiple "hits", thereby frustrating the repairer and devaluing the process [Bremer, 2000].

If the combination of rule-making and the proposed search facility comes to fruition, the following services to the repair market should result [Bremer, 2000]:

- Publishers would continue to serve those requiring paper copy.
- Diagnostic tool manufacturers would provide information about their tools.
- Repair information "portals" would emerge providing a "one-stop-shop" for information from many manufacturers and adding value through further guidance and the sale of suitable tools.

A "reasonable and non-discriminatory" fee would be payable for repair information and copyright rules would prevail. Preparatory work on this legislation was concluded in 2000. [Bremer, 2000]. One possible legislation trend is oil quality. Before oil can be changed the measured quality of oil must be low enough. Environmental impacts are obvious in this legislation.

2.2 The Process Industry

In the process industry the diagnostics term is less used. A more frequently used term is condition monitoring, which includes the diagnostics term. In the process industry preventive condition monitoring have been proven to lower the costs. Methods like thermal imaging, vibration analysis and oil analysis are long used tools.

The CAN-field-bus or J 1850 is quite dominant in the vehicle communication area. It is also a good choice for many mobile machinery applications. Hence various other bus specifications exist in the field of process automation. The most used are [Sink, 2001]

- PROFIBUS
- DP/PA,
- INTERBUS-S
- DeviceNet
- ARCNET
- AS-I
- Foundation Fieldbus H1

- Foundation Fieldbus High Speed Ethernet (HSE)
- IEC/ISA SP50 Fieldbus
- Seriplex
- WorldFIP
- LonWorks
- SDS
- ControlNet
- CANopen
- Ethernet
- Modbus Plus
- Modbus RTU/ASCII
- Remote I/O
- Data Highway Plus (DH+)

Many of these do not fulfil the requirements for mobile machinery. Continuous transfer speed and price of the hardware are the main reasons.

Standardisation in the field of condition monitoring is mainly focused on vibration measurement and oil condition monitoring (Appendix 2). The process industry also uses its own national standards in condition monitoring. One example is the Finnish process standard organisation PSK [PSK, 2002].

3 Sensors

A variety of different sensors are being attached to modern automotive vehicles in fast growing numbers. The need for comfort and diagnostic properties of machines are pushing developments in this direction. Sensors have taken big steps in technology. Methods like MEMS manufacturing have reduced prices and increased usability. Today's typical production car has 20 sensors of various types that use several different technologies. A high-end luxury car has over 60 sensors for tasks such as measuring the intake of manifold air pressure and detecting the presence of rain on the windshield [Frank, 2000].

When discussing mobile machinery it is reasonable to follow sensor technology in on-road vehicles for at least the following reasons:

- Technology investments in on-road vehicles are huge compared to mobile machinery
- Same Drivers also have an impact on the requirements of sensors
- Applications are easy to copy almost directly to mobile machinery
- Cost savings are obvious when using high volume on-road applications.

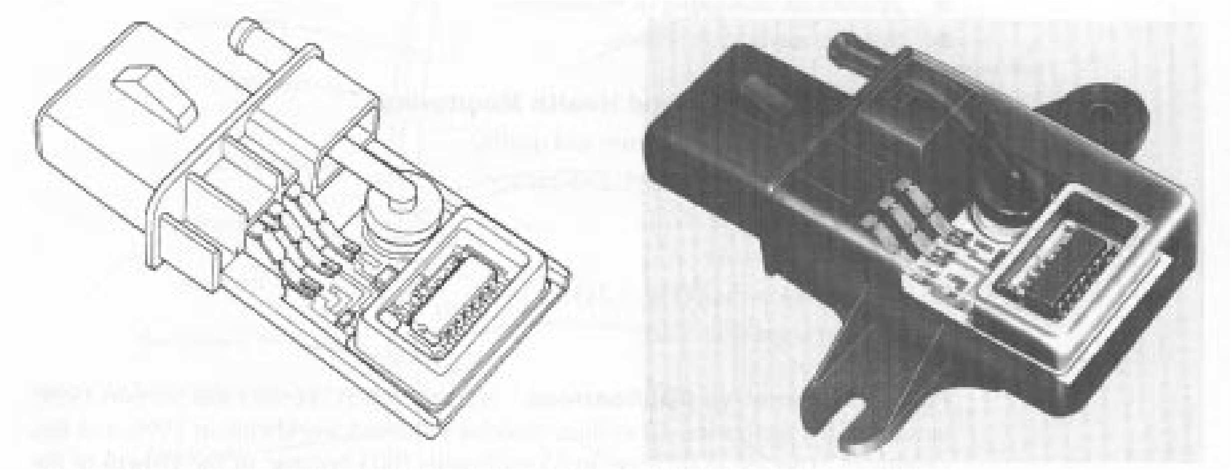


Figure 1. Silicon capacitive manifold absolute pressure sensor [Hsu, 2002].

3.1 Drivers for New Sensors

In the automotive section, three driving forces have significantly impacted sensors: requirements for driver information, legislation, and driver demands. In some cases, car manufacturers have designed electronic control systems to offer improved capability or a new feature, anticipating driver demands. In addition, the transition from electromechanical to electronic systems has been integral to these systems as well as the need to reduce warranty and complexity [Frank, 2000].

3.1.1 Informing the Driver

The earliest applications of sensors were derived from the driver's need for vehicle information. Sensors measured the amount of fuel, vehicle speed and critical engine parameters such as water temperature and oil pressure. Today's electronics combined with the latest sensing technologies can extend driver information by including other critical engine measurements that previously performed only periodically using manual techniques and sometimes required an expert to interpret results. These measurements include oil level and quality, as well as tire pressure. In fact, the number of measurements that can and will be made on future vehicles may cause information overload for the driver. Technology may also be used to handle the information and customise it to fit the driver's needs. Depending on drivers' preferences, the sensor information could be displayed continuously (i.e. road speed, oil pressure, etc.) or only when driver attention is required (low fuel, low tyre pressure, excessive coolant temperature) [Frank, 2000].

3.1.2 Legislation

New control systems demanded by legislation have usually meant new parameters to be measured and new technologies to build the sensors. The powertrain control system is the first electronic control system to use a microcontroller and a number of sensors. Figure 1 shows a typical engine and transmission or powertrain control system. The oxygen sensors use chemical sensing ceramic technology. The manifold pressure sensor can be silicon piezoresistive or ceramic or silicon capacitive, and the knock sensor is piezoelectric [Frank, 2000].

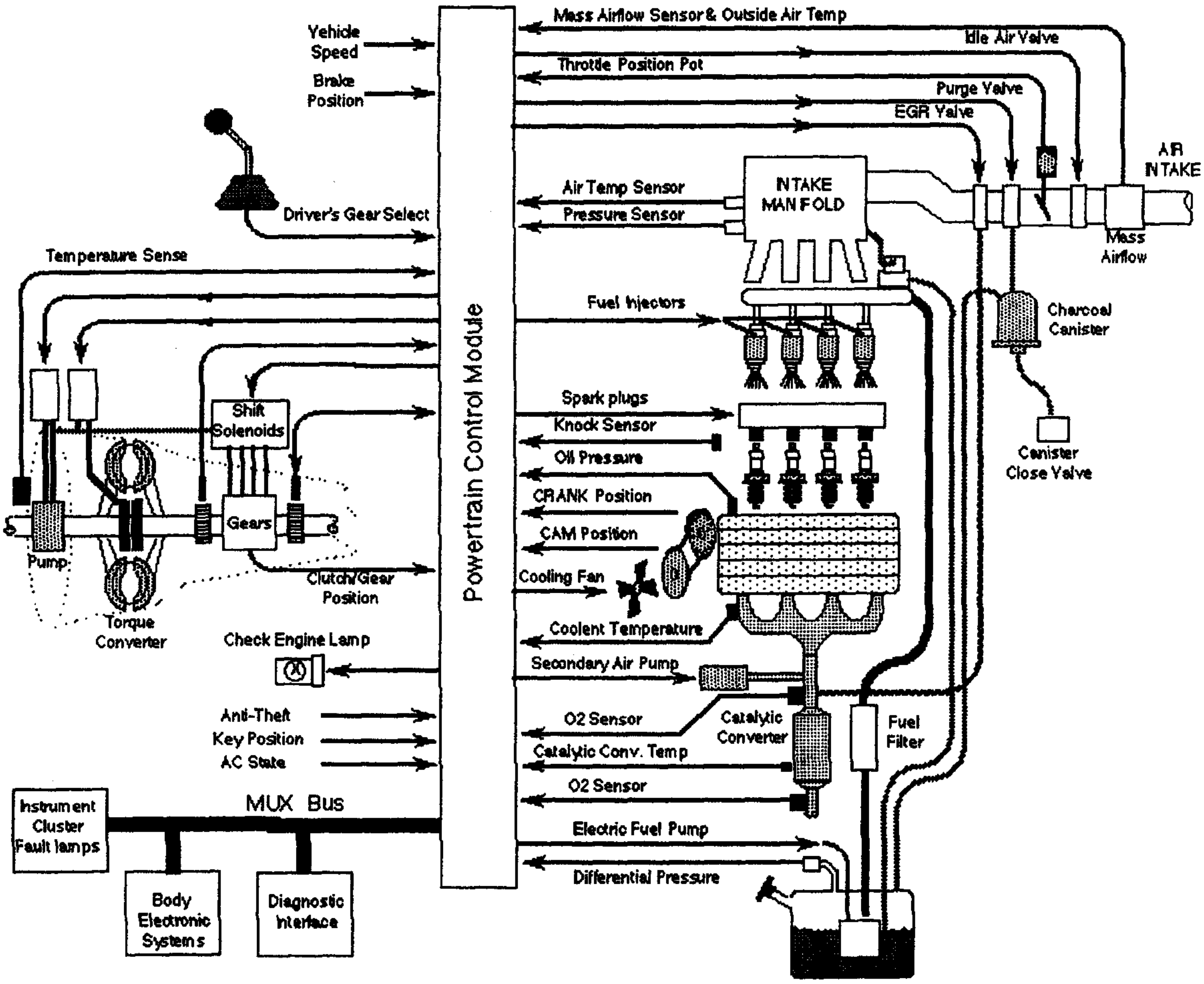


Figure 2. Sensors in an automotive powertrain control system [Frank, 2000].

3.1.3 Driver Demands

Ristic (1994) has listed potential sensor applications based on measurements during development or system operation that will be required in the future for automotive applications. Well over 100 measurements are identified (sensors used in electronic motor controls and entertainment systems are not included). Measurements suitable for condition monitoring are such as engine speed, oil pressure, oil level, oil quality, coolant pressure, coolant condition, coolant temperature, coolant level, transmission oil level (quality may also be available), transmission oil temperature and pressure, crank angle and position, torque, engine noise, battery fluid level, power steering pressure, steering wheel turns and position and so on. Some of these measurements are used for more than one system, indicating a need for multiplexing (MUX). Several "sensors" are simple switches that indicate system status [Frank, 2000].

3.2 Sensor Design for the Mobile Machinery Environment

3.2.1 The Automotive Environment

The automotive environment is recognised as one of the most difficult applications for electronic systems and for sensors, especially for microelectronic sensors. The mobile machinery environment is even more difficult. The minimum requirement for sensors in mobile machinery is to withstand the automotive environment. The automotive environment includes a wide temperature range, high humidity conditions, the need to withstand several chemicals, the ability to operate under high electromagnetic interference (EMI) conditions, to cause relatively low levels of radio frequency interference (RFI), and also the capability to accommodate wide voltage fluctuations. At the same time, the acceptance of electronics is extremely customer driven and demands low cost and high reliability. Sales volumes can decrease (or increase) quickly depending on customer acceptance of the system, the vehicle in which the system is offered, and external economic factors which affect purchasing decisions for high-cost items such as automobiles [Frank, 2000]. The same can be assumed to apply for mobile machinery as well.

One of the major differentiating factors for automotive usage is whether the location of sensors is in the passenger compartment or under the hood. Table 2 (after SAE J1211) shows the environment variations for electronic components. High temperature and humidity can significantly reduce the useful life, especially in underhood applications of electronics. The SAE (Society of Automotive Engineers) has developed SAE J1211 "Recommended Environmental Practices for Electronic Equipment Design" to address the unique problems of automotive electronics [Frank, 2000].

Table 3. The automotive environment [Ristic 1994].

Variable	**Underhood**	**Passenger Compartment**
Storage Temperature	-40°C to +150°C	-40°C to +85°C
Operating Temperature	-40°C to +125°C	-40°C to +85°C
Vibration	15g, 10 to 200 Hz	2g, 20 Hz
Humidity	Up to 100%	Up to 100%
Chemicals	Salt spray, water, fuel, oil, coolant and solvent immersion	---
Thermal Cycling	>1000 Cycles from -40°C to +125°C	>1000 Cycles from -40°C to +85°C
EMI Protection	Up to 200 V/m	Up to 50 V/m

The system voltage in passenger vehicles is nominally 12 V. However, several normal and abnormal voltage variations occur which must be taken into account at either the component or system level. Normal operating charging systems regulate the output of the alternator to attempt to provide sufficient voltage to keep the battery charged under various temperature and loading conditions. This voltage can range from 16 V when very cold (-40°C) to about 12 V when the maximum underhood temperature is reached. Electronic assemblies on the car must be able to withstand reverse battery conditions (-12 V), jumpstarts from tow trucks (24 V), short duration voltage transients (in the range of 1-100 V), and long duration (>400 ms) alternator dump transients which can be as high as 120 V. The load dump is clamped at some point or points in the system to restrict its maximum to a level of 60 V or less. To prevent damage due to excessive voltage, microelectronic sensors must have a regulated and protected power bus. The impact of higher system voltage in future vehicles will need to be evaluated for sensors [Frank, 2000].

The increasing complexity of modern vehicles has increased the possibility of EMI causing problems between the various vehicle systems. In addition, electronics can be susceptible to or may radiate RFI, causing poor radio reception and malfunctioning vehicle systems with a resulting no-fault condition found during service diagnostic procedures [Frank, 2000].

3.2.2 Sensor Packaging

The sensor packaging problems specific to the application must be thoroughly addressed to ensure acceptable performance over the sensor's expected lifetime. One approach is described in a recent paper [Maudie et al, 1997]. Identifying minimum expectations and critical application factors that limit device lifetime is part of a methodology known as the *physics of failure* approach to reliability testing. It involves analysing potential failure mechanisms and modes. Once these are understood, application-specific packaging development can proceed, the proper test conditions can be established, and critical parameters can be measured and monitored [Maudie et al, 1997].

A specific failure mechanism in harsh media applications is corrosion, mainly galvanic corrosion caused by dissimilar metals that are in electrical contact in aqueous solutions. Using a physics of failure approach, one may ask the appropriate questions: Which environmental factors contribute to the failure mechanism? What accelerates it? What should be done to the sensor package to prevent corrosion or minimise its impact over the sensor's lifetime? What is the expected sensor lifetime? The answers to these questions allow simulations to be performed and costs to be analysed before lengthy and potentially expensive testing is initiated. The testing will ultimately prove the acceptability of a particular proposal. Unless the proper mechanisms are known, over-designing can add unnecessary cost to the packaging, such as a passivation layer, a hard die attachment, or any non-standard process. Furthermore, the design tradeoffs that result may not prove beneficial. For example, adding a hard die attachment for a pressure sensor to improve the strength of the die bond could limit device performance in other areas such as the temperature coefficient of offset [Maudie et al, 1997].

3.2.3 Improving Sensor Performance

The low-level output of most sensors and the requirement to meet specifications over a wide operating range are among the problems that must be solved to use a sensor in a particular application. Table 5 summarises some of the common shortcomings of sensors and how electronics is used to overcome these limitations [Frank, 1996]. Improved sensor performance can result when the design of the sensor and capability of subsequent components are taken into account in the overall design of the sensor. Digital logic provided by either an MCU (microcontroller unit) or DSP (digital signal processor) plays a vital role in smart sensing and in improving the sensor's performance [Frank, 2000].

Table 4. Common undesirable sensor characteristics and improvement techniques [Frank, 1996].

Characteristic	Sensor Design	Sensor Interface	MCU/DSP
Non-linearity	Consistent		Reduce
Drift	Minimise		Compensate
Offset		Calibrate	Calibrate/reduce
Time dependence of offset	Minimise		Auto-zero
Time dependence of sensitivity			Auto-range
Non-repeatability	Reduce		
Cross-sensitivity to temperature and strain		Calibrate	Store value & correct
Hysteresis	Predictable		
Low resolution	Increase	Amplify	
Low sensitivity	Increase	Amplify	
Unsuitable output impedance		Buffer	
Self-heating	Increase Z		PWM technique
Unsuitable frequency response	Modify	Filter	
Temperature dependence of offset			Store value & correct
Temperature dependence of sensitivity			Store value & correct

Considering wireless systems the development of smart sensor technology has a vital role. There exist limitation of wireless systems ability to move the volumes of data that are generated at the sensors in a CBM (Condition Based Monitoring) system, particularly vibration sensors. The smart sensors make it possible to reduce the data at the sensor and send useful information to the next level in the CBM system. The smart sensor collects the data, converts analog signals to digital, performs an array of digital signal processing and software functions to provide the operator with information which contributes directly to the determination of the remaining useful life of the component being monitored.

3.2.4 Technologies

The critical design aspects for automotive sensors can be divided into three areas: the transducer element, interface electronics, and packaging. The basic transducer element is expected to meet the performance requirements of the system and be able to tolerate the normal over-range occurrences that could be anticipated in certain failure modes of other components. The output should be stable over the operating temperature range and the lifetime of the vehicle. As mentioned earlier, electronics is frequently required to enhance the output signal; calibrate the zero and sensitivity; compensate for the effects of temperature and other variables; tolerate electromagnetic interference; provide protection for short circuits, reverse battery and other voltage conditions; and increasingly to provide diagnostic and self-test features. The ease of interface for digital processing also requires the output of an analogue sensor to be converted through an (integral) analog-to-digital interface or serial communication interface. The sensor package required for the automotive environment must be small; easy to handle and mount in the application; extremely robust and capable of withstanding thermal cycling, thermal shock, vibration, and various chemicals and high levels of humidity; and provide the EMI protection for the sensor and interface electronics [Ristic, 1994].

Progress is being made in several areas for sensors in future vehicles. These improvements are targeted to basic sensing techniques, manufacturing processes, the sensor interface (both electronic and mechanical) and resonant beam, and interdigitated structures should be used for both sensing and actuating. More advanced deep photolithography techniques, such as the LIGA process, will add new sensor structures and performance capability to future sensors [Frank, 2000].

Most sensors address only one parameter, although temperature information is frequently derived simultaneously. In the future, multiple sensors created on a single sensing chip will be more common. These will include sensors such as tri-axial accelerometers to sense three directions on a single chip or sensors for different functions such as combined pressure, temperature, humidity, and vibration sensors for HV AC (heating, ventilation, and air conditioning) applications. The cost of designing an additional separate sensor will be greater than simply including the sensor with other devices on the same chip. From a manufacturing perspective, proper design means that the process complexity does not increase due to addition of the new sensor. The additional material for the sensor will be insignificant compared to existing sensors and especially to the electronics already required for interfacing, calibrating, and adding intelligence to the other sensor(s). Sophisticated testing will determine which sensors are ultimately used for a particular system. This is the point where cost increases will occur. However, it is also the point where value will be added to the sensor [Frank, 2000].

3.3 Oil and Vibration Monitoring

3.3.1 Vibration Monitoring

Vibration (acceleration, velocity) sensors have been around for a long time. Problems have until recently been in signal processing and interpretation of signals. Equipment has been too expensive and extensive for on-board applications. The price and size of equipment have diminished alongside other electronics, so on-board systems are now one option in monitoring. In standing machines of the process industry, vibration-monitoring targets are big rotating elements like turbines and reels of paper machine. This area is highly standardised. There are at least standards dealing with the diagnostics of hydraulic pumps, mechanical drives, journal bearings and roller bearings [PSK, 2000]. Some mobile machinery uses very large diesel engines. For example, in some applications it could be reasonable to monitor some large motor components with vibration sensors. Data like natural frequency changes of engines and fault frequency values of bearings could prove valuable to service personnel and even to machine operators if enough measurement intelligence is added. Now that vibration measurement equipment is becoming less costly, it is reasonable to monitor increasingly smaller components.

3.3.2 Oil Analysis

Oil is an important lubricating component in a machine system. Oil analysis is a method to monitor lubrication. In off-line oil analysis the oil sample is tested in the laboratory. On-line analysis measures a proportion of the oil by direct connection and is then returned to the system. In a method known as in-line analysis, all the oil that passes through the system is measured [Hunt, 1996]. Off-line engine oil analysis is a tool that is used widely in mobile machinery. Some examples are CSA (customer support agreement) by Caterpillar [CAT, 2002] and ProAct by Partek Forest [Partek Forest, 2002]. Here the machinery manufacturer monitors, among other things, the oil condition in the machine with regular off-line analyses. This is tedious to the manufacturer and costly to the end-user, so in-line and on-line quality sensors are being developed. Mainly this is driven by the automotive industry due to the environmental impact of oil-change optimisation. Table 6 lists some of the properties that can be measured from oil.

Mainly one method has been implemented to a commercially ready on-line sensor. This is water-content measurement by dielectric constant capacitance. There are also various other types of water content measurements [Hunt, 1996]. Sensor manufacturers have noticed that the dielectric constant value indicates also other properties in oil, like additive depletion, changes in total acid number and viscosity. These are all key parameters in determining oil condition. One drawback of this sensor is that it is temperature dependent. This is why sensor manufacturers have integrated temperature and oil level measurements in their sensors, in order to better interpret the dielectric value [Delphi Automotive Systems, 2002; Temic, 2002]. Another approach is to measure the pH of the oil, which also indicates its condition. This on-board oil sensor development is at the research stage [DeGaspari, 1999].

Table 5. Oil properties which can be monitored [Hunt, 1996].

Property	Units	Description	Comments
Viscosity (kinematic)	mm^2s^{-1}	A measure of the oil's resistance to flow	Oil viscosity drops substantially with rise in temperature
Viscosity index (VI)		A measure of the oil's resistance to dropping viscosity	From 0 to 300; the higher the value the less change of viscosity with temperature rise
Density (ρ)	kgm^{-1}	A measure of the oil's mass per unit volume	Typical oil would be from 880 kgm^{-3} (20°C) to 830 kgm^{-3} (100°C), varying with pressure
Total acid number (TAN)	mg KOH g^{-1}	Amount of potassium hydroxide neutralising 1 g acid sample	Increases with oxidation and in the presence of high sulphur diesel fuels
Total base number (TBN)	mg KOH g^{-1}	Acid equivalent to KOH needed to neutralise 1g base	Included to restrict acids in their corrosive effect
Water content	ppm	Dissolved, but at higher levels may form a fine dispersion of droplets	Unhelpful both for the power fluid and for the lubricant (even at 100 ppm)
Pour point	°C	Lowest temperature at which the oil will just pour from a container	Oils are normally used at least 10°C above the pour point
Flash point	°C	Temperature at which vapours given off ignite in presence of a flame	Typically between 150°C and 250°C for a mineral oil

A different approach to monitor engine oil quality has been developed by General Motors Corp. It is not based on quality sensors, but on a mathematical model that uses the engine's computers to infer the rate of oil degradation from data already being collected by various systems within the vehicle. The advantage of this "driving habits" system is lower cost. A combined approach of monitoring driving conditions and using sensors has been taken by DaimlerChrysler. The system is called Assyst and it is installed optionally in new Mercedes-Benz vehicles [DeGaspari, 1999].

3.3.3 Wear Debris Monitoring

In big mobile machinery, the powertrain from combustion engine to actuators is usually arranged with hydraulics. This is due to high-power and low-weight demand. The hydraulic pump is operated through a diesel engine. The pump allocates power to the driving hydraulics, actuator hydraulics, brake hydraulics and possible other hydraulic accessories. If the driving speed is high, the mechanical powertrain is usually applied.

Hydraulic oil can be monitored with the same methods as engine oil. In engine oil there are sour burning deposits like soot, which does not occur in hydraulic oil. VTT has performed some experiments in which hydraulic oil degradation was measured with a dielectric sensor.

At the time, the results were not convincing [Mustonen, 2000]. Some of the process industry's detection instruments for water in oil could be useful to hydraulic oil monitoring, like the HMP228 on-line detector by Vaisala [Vaisala, 2002].

A special option for machinery components is to monitor the amount of wear debris in the system. Wear debris can occur as a result of adhesion, abrasion, fatigue and tribochemical reaction. Wear debris detection methods include the following: [Hunt, 1996]

- Electrical sensing zone
- Electroacoustics
- Filter blockage
- Inductance of oil and magnetic methods
- Optical methods, such as Fraunhofer diffraction, light obscuration and time of transition
- Wear of thin film (Fulmer)

In hydraulic systems this could enhance monitoring. With engine oils, small pieces of burning deposits reduce the efficiency of wear debris detection. Water and air bubbles in oil are drawbacks also when using optical detection methods. Monitoring the amount of wear debris is often performed by machine manufacturers through service agreements as an off-line method alongside oil analysis. These off-line instruments have been in use for decades.

On-line instruments for monitoring the amount of wear debris in oil have also been developed. They are usually based on optical methods. One has been developed by Hydac [Hydac, 2002] with Caterpillar Inc. This is meant more to be used in hard environments and is rather expensive. Other manufacturers include PSI [PSI, 2002] and Parker [Parker, 2002]. These instruments are not meant to replace laboratory off-line testing, but to give the operator a better view of the machine's state. PSI's HIAC sensors are very cost effective. Both these and HYDAC monitors also have direct fieldbus links. The HYDAC sensor even has a direct CAN link.

The next step is to take wear debris and examine it optically on-line (some instruments available) or with a spectrometer. The shape and colour give indication of wear mechanism and fault location in the machine. The elementary composition of the debris can be characterised with a spectrometer. Although no in-line commercial instruments are available for this, some prototypes have been built in this area [Saba and Wolf, 2000].

Figure 3. HYDAC (left) and PSI HIAC (right) on-line oil particle counters [HYDAC, 2002; PSI, 2002].

3.4 New Sensor Technologies

Many emerging sensing techniques are in the development phase. New technologies utilise advanced materials, radar, infrared, chemical, and even next-generation magnetic sensors. Silicon is being used for electronic components in vehicle systems including computing, power control, transient suppression, and sensing. However, other materials operating at higher frequencies and/or temperatures are also being explored for sensor in-vehicle applications. Gallium arsenide and silicon carbide are two examples of advanced semiconductor materials [Frank, 2000].

Other advanced materials include polymer films and ceramic materials in which the piezoelectric effect is present. Piezoelectric materials convert mechanical stress or strain into electrical voltage. These materials also expand or contract when a voltage of opposite polarity is applied. As a result, a sensing and actuating combination can be achieved [Frank, 2000].

A micromachined calorimeter has been developed to detect extremely subtle chemical reactions on surfaces. The monolithic combination of many different such sensors to serve as a "nose" for detecting multiple chemicals is among future possibilities [Frank, 2000].

Infrared sensors are at the heart of night vision systems. Near infrared sensors and head-up displays provide vision enhancement for night-time driving. Information from the sensors requires real-time processing to display images to the driver. The improved vision is needed to reduce accidents, especially those involving pedestrians [Frank, 2000].

Magnetic sensing has evolved from reluctance to Hall effect sensors. Magnetic resistive elements using materials such as permalloy, a ferromagnetic alloy composed of 20% iron and 80% nickel, are being developed and are already in use in vehicles. Continued R&D efforts to find a low-cost solution for speed sensing, especially at very low speeds, should provide some interesting sensor technology for future vehicles [Frank, 2000].

Research has been performed using quartz resonators in direct contact with the fluid to measure changes in liquid density and viscosity. With this technology not only oil quality, but also the capacity of coolant and the state-of-charge of lead acid batteries could be monitored. This research was performed by Sandia National Laboratories, General Motors and Delphi Automotive [USCAR, 2002]. Sandia National Laboratories have also carried out research into engine particulate counters, pressure monitors, fuel vapour sensors, fluid monitors and rotation/position sensors [Sandia National Laboratories, 2002].

4 Vehicle Networks

A one development trend in vehicle networks is wireless communication. Wireless applications have the following advantages and benefits [Wunderlich et al, 2000]:

- Reliability
    - No wiring in problematic areas
    - No connectors
    - High corrosion resistance
    - Robust against mechanical vibrations
    - High availability
- Flexibility

  - Design and re-design flexibility
  - Easy to modify
  - Extension capability
  - Supports trend towards decentralisation
  - Avoidance of lead-throughs
- Costs
  - Simplified cable harness
  - Easy to mount (mechanical connection, electrical connection, good accessibility, easy to handle, easy to automate)
  - Easy to service
  - Standardisation of components

In the mobile machinery sector, one possible trend is the service-centre concept, which is being used within the process industry [Kainu, 2000]. This concept requires special attention on wireless communication. It makes sense to follow network technology trends for on-road vehicles when discussing mobile machinery, for the same reasons as with sensors (Headline 3).

4.1 Vehicle Inside Networks

In order to ensure the necessary exchange of information for reliable and safe vehicle operation and also for diagnosis, a large number of today's most modern vehicles have their electronic components and systems interconnected through suitable network structures. Communication networks, usually in the form of serial bus systems, enable the collection and transfer of most of the required diagnosis data for both on- and off-board diagnostics [Bremer, 2000].

Figure 4 shows a serial bus structure that is already installed in a large number of small and medium sized road vehicles. This form of bus structure will be installed in all new vehicles of this category in the future [Emaus, 2000a].

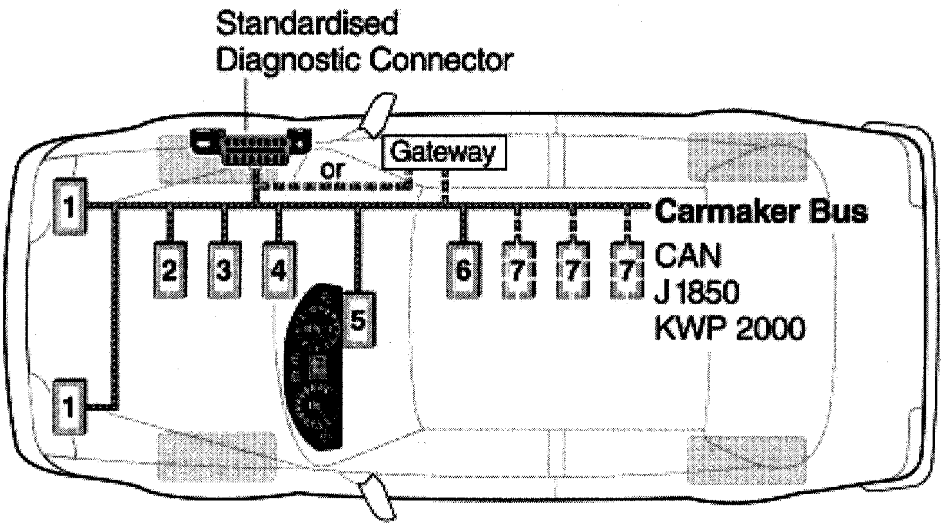


Figure 4. Typical basic vehicle network [Emaus, 2000a].

The vehicle bus is connected (directly or through a gateway) with a standard plug that permits the connection of external testing and diagnostic equipment (for the workshop, for roadside repair organisations, for approval authorities, and for roadworthiness tests). This equipment will be able to read out data from the vehicle as well as to input data into it (e.g. end-of-line programming and software updating) [Bremer, 2000].

In the past, a separate data line (ISO 9141-2) was often used for purely diagnostic applications. It was active only when an external scan tool was connected to the vehicle with the diagnostic connector and initiated a diagnostic session or a software update to the vehicle ECUs. A second bus was used for data transfer between ECUs (for instance, the ECUs for engine management and gearbox) as needed for ensuring the correct operation of the various vehicle functions. This bus data transfer rate was in the range of several 10 kBaud - 500 kBaud. Since the Controller Area Network (CAN) protocol has emerged as the global standard, diagnostic data has been transferred through the ECU bus. The vehicle bus was connected to the diagnostic connector either directly or through an electronic interface (gateway) [Bremer, 2000].

The vehicle bus is also connected to the driver's information centre on the instrument panel. All of the necessary information is presented in a suitable form without distracting the driver from his main function: control of the vehicle. This presentation of data makes full use of present day know-how from the human machine interface (HMI) sector [Bremer, 2000].

Figure 5 shows an example of a system and data structure currently found in modern comfort-class vehicles, and expected to be in all such vehicles in the future. A number of buses with varying technical requirements, structures, and speeds from the areas of telematics, multimedia, and other applications are integrated in the typical vehicle network [Emaus, 2000b].

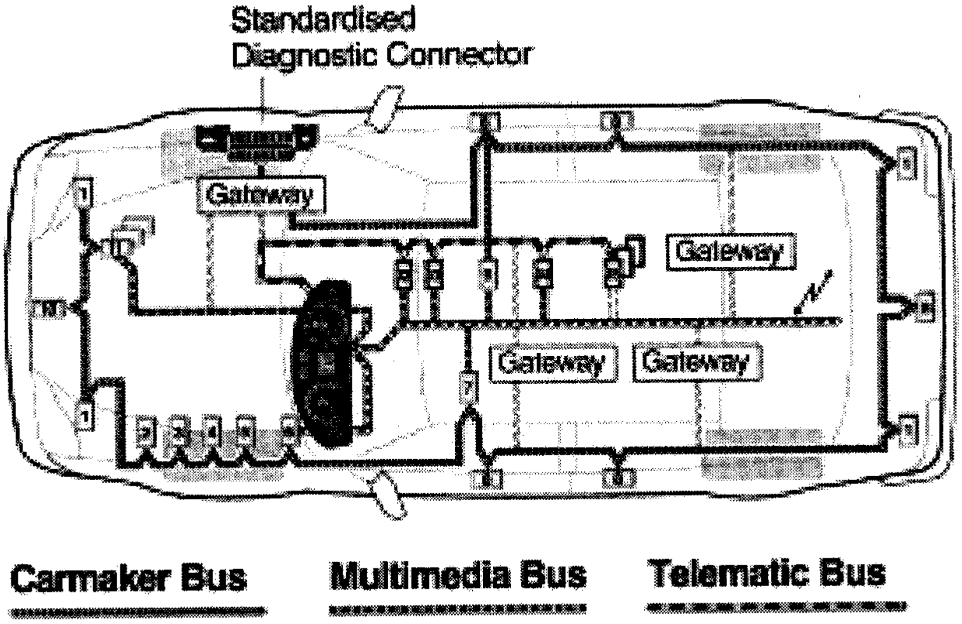
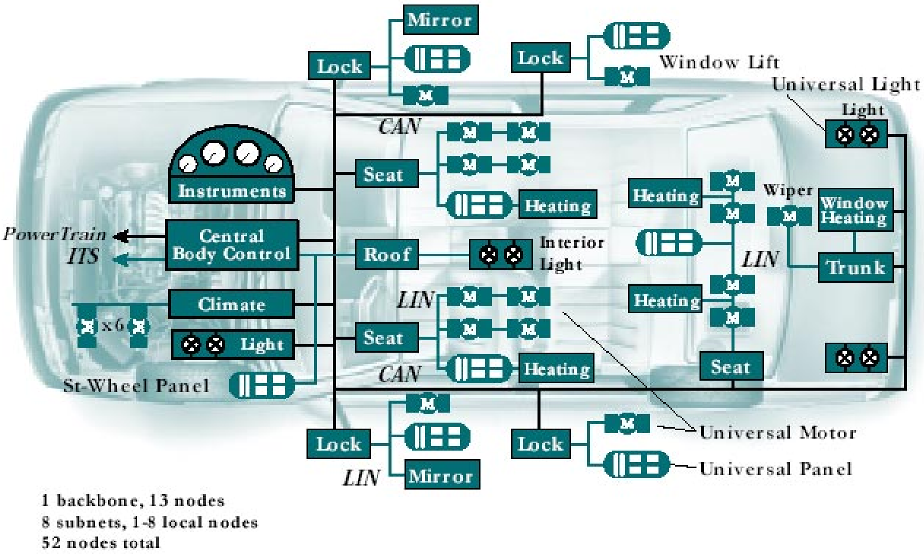


Figure 5. Example of several serial networks in a luxury vehicle [Emaus, 2000b].

Depending upon the data transfer speed, buses will be using optical data transfer principles [Saito et al, 1998]. State-of-the-art telematic buses will also implement wireless data transfer to the infrastructure of a road, highway or region [Powers et al, 1998]. Intranets or the Internet may also be included [Bucley et al, 1998]. Even with such comprehensive network structures in the vehicle, a single connection will be used through a diagnostic connector for the external off-board diagnostic tools [Bremer, 2000].

Gateways, bridges, and routers interconnect the various networks and enable the relevant data for the vehicle diagnosis to be available at a central point. This point will either be on the instrument panel for informing the driver as required or via the diagnostic connector for external applications as already mentioned [Bremer, 2000].

As CAN is considered to be too costly for some simple automotive devices, a new bus specification called Local Interconnect Network (LIN) has been introduced by Audi, BMW, DaimlerChrysler, Motorola, Volcano Communications Technologies (VCT), Volkswagen, and Volvo. Microchip actively supports LIN, for example by providing microcontrollers with an integrated LIN transceiver. LIN is not aimed to replace CAN but to complement it as shown in Figure 6. [Motorola, 2002]



1 backbone, 13 nodes
8 subnets, 1-8 local nodes
52 nodes total

Figure 6. Example of an automotive bus architecture using LIN [Motorola, 2002].

Another low cost sensor-actuator bus specification is TTP/A. It has been developed by the University of Vienna group (professor Herman Kopetz). TTP/A is based on Universal Asynchronous Receiver Transmitter (UART) communications and thus resembles the LIN bus [TTPforum, 2001].

It is possible to make a control and monitoring system without using a single wire in the vehicle. Equipment for wireless sensor networks is available. Crossbow Technologies Inc. have integrated a Bluetooth wireless component in a sensor [Crossbow Technologies, 2001]. Various problems still exist, however, with wireless sensor networks. The greatest is the power feed to the system. Other examples are EMI and RFI requirements for sensor information. The price is higher due to lower volumes. However, some new sensors must be implemented through wireless nodes. Tyre pressure monitoring is an obvious example [Nokian renkaat, 2002].

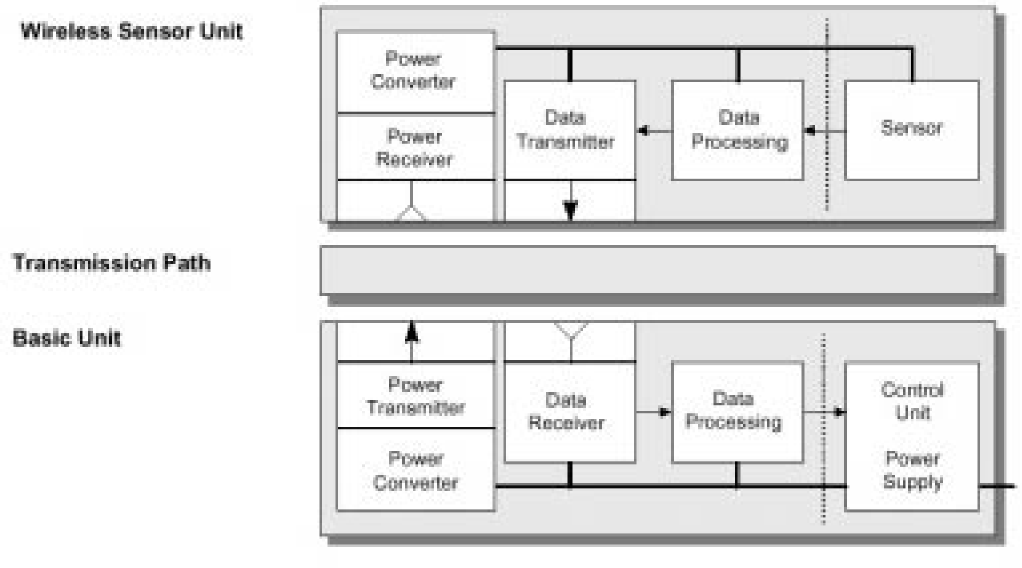


Figure 7. Architecture of a wireless sensor unit with information and power transmission [Wunderlich et al, 2000].

4.2 Wireless Short Distance Networks

Communication distances are defined in figure 8. Wireless short distance networks are used in distances under 100 m. WLAN and Bluetooth standards operate in this area. Use of these standards in short distance communication is recommended, since there is no operator data fee. Both WLAN and Bluetooth standards operate on 2.4-2.5 GHz frequency band. Some mention has been made of possible interference in these standards [Mobilestart, 2002; Oraskari, 2002]. A new standard in the USA, 802.11 (fast WLAN) uses the 5.15 GHz to 5.35 GHz frequency band. Data transmission speed is increased from (WLAN) 11M bit/sec to 54M bit/sec. In Europe a similar HIPERLAN standard (High Performance Radio LAN) is emerging to hardware level. In addition to 2.4-2.5 GHz another ISM-band (industrial, scientific and medical) using 0.902-0928 GHz frequency is worth mentioning. Crossbow Technologies Inc. has constructed a wireless sensor network using this band [Crossbow Technologies, 2002]. With correct antennas the WLAN communication area can be even greater.

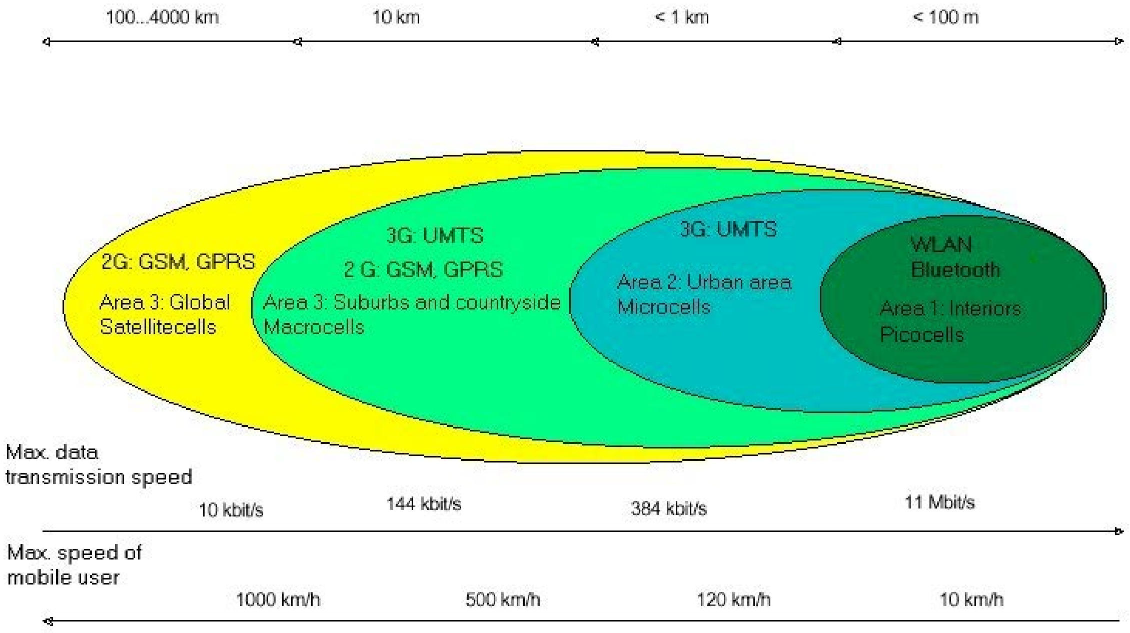


Figure 8. Area definition in wireless communication [Airenne, 2001].

A future model of a wireless service station for automotive section is sketched elsewhere [Wunderlich et al, 2000]. Wireless communication between the vehicle and a computer at the service station can be used to exchange status information and service specific information. This step may be supported by a preceding data exchange using telecommunication. Wireless communication in combination with a mobile service computer offers optimum flexibility to service personnel. The mobile computer is connected to the computer of the service station as well as to the vehicle controller. During service all single units and subsystems of the vehicle are checked, functions are adjusted, and new sets of parameters or new versions of software are downloaded to the vehicle if necessary. A similar concept may be easy to transfer also to mobile machinery [Wunderlich et al, 2000].

4.3 Wireless Long Distance Networks

As the communication distance becomes longer the use of international network systems for radio telecommunication is an obvious choice. First generation systems could not transfer data because they were based on interfered analogue signal transfers. NMT (Nordic Mobile Telephone), AMPS (Advanced Mobile Phone Service) or TACS (Total Access Communications Standard) are some examples of analog standards. The digital secondgeneration systems include well known GSM (Global System for Mobile Communications), CDMA (Code Division Multiple Access) and less known NADC (North American Digital Cellular) standards. With improved GSM+ or CDMA+, data transfer and SMS messages (Short Message Service) became possible. The transmission speed in the GSM standard is 9600 bit/s. With HSCSD technology (High Speed Circuit Switched Data) this is increased to 14.4 kbit/s. GPRS (General Packet Radio Service) technology allows a maximum of 170 kbit/s. With a technology called EGPRS, the theoretical data speed could be increased to 384 kbit/s. The GPRS standard is often referred to as second and half generation networks. Third generation standards such as UMTS (Universal Mobile Telecommunication System) allow transfer rates as high as 2 Mb/s. Operating frequencies and frequency bandwidths are controlled by each country’s authorities. [Joronen, 1998; Penttinen, 1999]

In the paper industry a service centre concept is arising interest. Remote diagnostics allow collection, transfer and analysis of essential data. Systematically collected data can be utilised as pre-information for maintenance as well as in a preventive/predictive way when analysing the condition of the machinery and process. In the process industry the data could be transferred through telephone lines using ordinary modems and Internet. This is not possible in the case of mobile machinery if a fast response time is needed. Another possibility to collect data without wireless connection is to connect a local mobile machinery service centre to an international remote centre. Again the local service centre could operate in the manner outlined in 4.2. A wide variety of wire and wireless solutions are possible to design for monitoring mobile machinery.

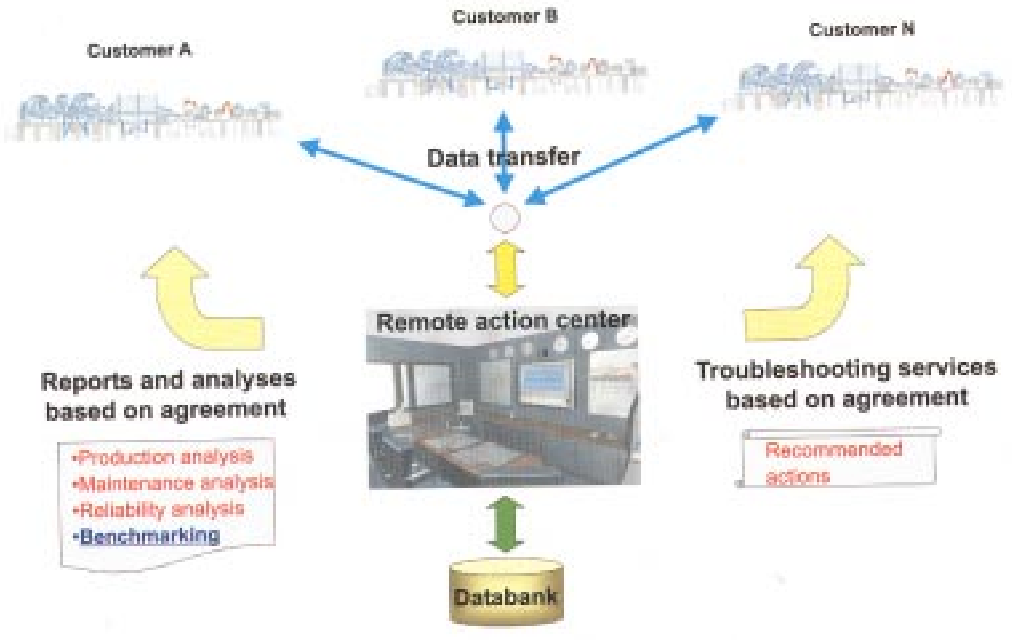


Figure 9. Remote action centre-concept in the paper industry [Kainu, 2000].

5 Methods for Data Analysis

Tomorrow’s data analysis systems will be intelligent and adaptive. At present mainly boundary values are used in diagnostics; tomorrow they will move according to environmental changes and the learned self-characteristics of the machine and its user. New areas of signal processing are also possible to add to the vehicle diagnostics system. Some examples are wavelets and blind signal processing. [Polikar, 2000; Cichocki and Amari, 2002].

5.1 Artificial Neural Networks

Artificial neural networks (or nets) are methods of processing signals and other information, which are based on data processing of presumed biological nerve systems. High data element connectivity is typical for neural nets, which is the reason they are called 'nets' [Kohonen, 1998].

Data processing by neural nets became possible along with improved calculation power of computers in the late 1980s. Measured knowledge is essential for neural calculating. Usually this is done by teaching a desired function through examples. Non-linear dependence of parameters can be taught directly from measured signals, other observations or statistics. The operation principle is therefore different from using rules or physical laws in calculation [Kohonen, 1998].

Neural nets consist of simple calculating elements called neurons. Each neuron has many inputs and only one output. Typically every neuron has a weighting factor which strengthens or weakens, and the output of the neuron is calculated from weighted factors. The neuron and multilayer neural net structure is described in figure 10. The three most used activation functions are described in figure 11 [Kohonen, 1998].

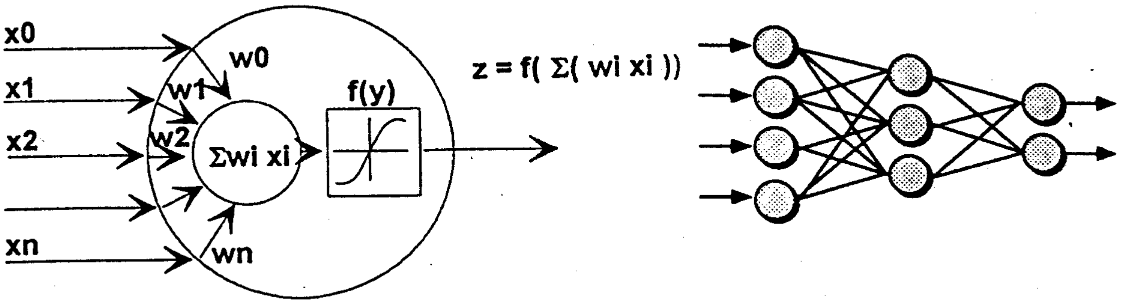


Figure 10. Construct of neuron and multilayered network, where x is the input, w the weight factor, $\Sigma w_i x_i$ *the multiplied sum of inputs and weight factors, f(y) the activation function and z the output [Kolinummi et al, 1996].*

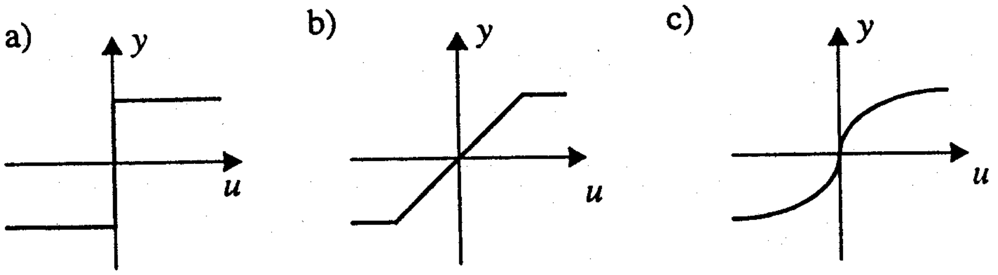


Figure 11. Plots of activation functions: a) step function, b) segmented linear function c) sigmoid-type function [Kolinummi et al, 1996].

The most vital task in neural calculation is defining weighting factors. This is usually done by teaching. At the beginning the weighting factors can be guessed. Teaching is done by constantly applying examples from measured quantities and the right answers [Kohonen, 1998].

Classification of fruits may be used as an example of how neural nets operate. We choose an apple, banana and orange. The classification features for fruits are shape, taste and colour. Input is a number feature. It may be between zero and one. For example, if the number for ‘shape’ is one, the target is fully round. If the number is zero, the shape is oblong. Features of the fruit are given to the net, and it calculates with the present weight factors an answer for the fruit. If the answer of the neuron is too small or big the weight factors will be changed. [Koikkalainen, 1994]

Neural nets may also be classified by topology. Each topology is used in different types of problems. Most applications of neural networks fall into five categories: prediction, classification, data association, data conceptualisation and data filtering (Table 7) [Anderson and McNeill, 1992].

The University of Manchester has carried out research into neural nets in fault accommodation for a diesel engine sensor system. As mentioned above there are many sensors used in engine control. A fault in any of these sensors may develop a system failure causing the engine to stop. This has led to the design of a fault tolerance sensor system. Fault tolerances can be achieved by hardware or analytical redundancy. As most engine parameters are related to each other, information about one parameter can be obtained from the others. This characteristic can be used to create analytical redundancy, which can be employed to accommodate sensor failures. Neural nets are very appealing for this purpose due to their learning and adaptation capabilities. The benefit of this research is that part of the redundancy hardware (duplicate sensors) can be replaced by neural network software, which diminishes the total cost [Badri et al, 2001]. Similar research has been done by the University of Perugia with the help of FIAT [Grimaldi and Mariani, 2000a, Grimaldi and Mariani 2000b].

DaimlerChrysler have researched neural nets in misfire detection. In this method, a dynamic neural network with output feedback is utilised to model an inverse system from the engine crankshaft speed signal to the firing event signal. The engine misfire detection is based on the output of the inverse system given the input of the engine speed signal. Test results were promising for a 4-cylinder engine [Wu and Lee, 2000]. A study of knock detection by neural nets has also been performed [Ortmann et al, 2000].

Table 6. Types of neural networks, used topologies and typical use of network [Anderson and McNeill, 1992].

Network type	Network topology	Use for network
Prediction	• Back-propagation • Delta Bar Delta • Extended Delta Bar Delta • Directed random aearch • Higher order neural networks • Self-organising map into back-propagation	Use input values to predict some output (e.g. pick the best stocks on the market, predict weather, identify people with cancer risks etc.)
Classification	• Learning vector quantization • Counter-propagation • Probabilistic neural networks	Use input values to determine the classification (e.g. is the input the letter A, is the blob of video data a plane and what kind of plane is it)
Data association	• Hopfield • Bolzmann machine • Hamming network • Bidirectional associative memory • Spation-temporal pattern recognition	Like classification but it also recognises data that contains errors (e.g. not only identify the characters that were scanned but identify when the scanner isn't working properly)
Data conceptualisation	• Adaptive resonance network • Self-organising map	Analyse the inputs so that grouping relationships can be inferred (e.g. extract from a database the names of those most likely to buy a particular product)
Data filtering	• Recirculation	Smooth an input signal (e.g. take the noise out of a telephone signal)

5.2 Fuzzy Systems

Fuzzy logic has been developed for approximate reasoning, when system parameters are not known precisely. This happens often in real life situations. Fuzzy logic is only one part of fuzzy based data processing, so it is better to discuss fuzzy systems [Koikkalainen, 1994].

Fuzzy systems are built by using fuzzy rules, which are scaled by numbers continuously between one (true) and zero (not true). The synergy between rules defines the final answer. Fuzzy set F in set space U is categorised by membership functions $\mu_f: U \rightarrow [0,1]$. Fuzzy set F in U can be presented by sets of pairs, which are made of generic elements u and their values of membership functions [Lin and Lee, 1996]:

$$F = \{(u, \mu_f(x)) | u \in U\} \tag{1}$$

where μ_f = membership function of F
$\mu_f(x)$ = degree of membership in set F

Figure 12 shows the strength of a decision describing the use of membership functions. This is used most in the fuzzy approach.

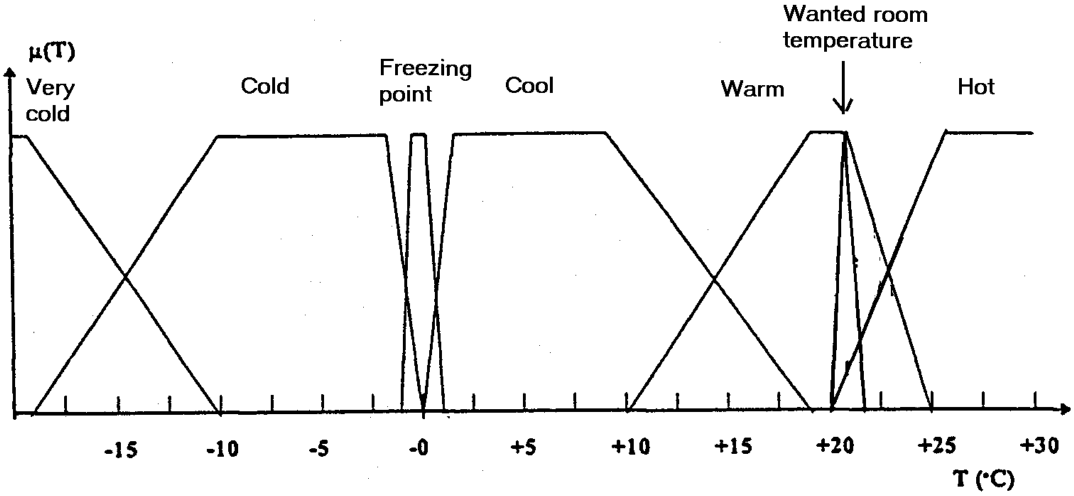


Figure 12. Visualisation of temperature by fuzzy sets, where $\mu(T) = [0,1]$ is the membership function's value at temperature T [Puolakka, 1997].

If we categorise the example in figure 12 with negative variables, we get:

F(temperature) = {very cold, cold, freezing point, cool, warm, wanted room temperature, hot}

Every term in set F (temperature) is fuzzy set in set space U = [-20, 30]. One can define the "wanted room temperature" to be "temperature of about 21°C". In figure 7 the shape of the membership function e.g. in "wanted room temperature" is triangular and in "hot" trapezoidal.

If the fuzzy sets of figure 7 are parameters of a fuzzy control system of room temperature, one can think that when it is cold, heating is efficient, and when one is in the cool area, heating is normal. In a situation where there is a wanted temperature, there is no temperature change and in the hot area one uses normal cooling [Taipale and Jurva, 1999].

In the automotive sector fuzzy logic has found increasing applicability in the field of vehicle control. Applications include automatic transmission, engine control, cruise control, anti-skid braking, and air conditioning, among others [Aptronix, 2002]. If the control system is based on fuzzy logic it increases pressure to design the diagnostic system also using fuzzy rules [Lu et al, 2000].

5.3 Genetic Algorithms

Genetic algorithms (GAs) are optimisation techniques based on the concepts of natural selection and genetics. GAs are a relatively new method in the area of data analysis. In this approach, the variables are represented as genes on a chromosome. GAs feature a group of candidate solutions (population) on the response surface. Through natural selection and the genetic operators mutation and recombination, chromosomes with the best fitness are identified. Natural selection guarantees that chromosomes with the best fitness will propagate in future populations. Using the recombination operator, the GA combines genes from two parent chromosomes to form two new chromosomes (children) that have a high probability of having better fitness than their parents. Mutation allows new areas of the response surface to be explored. GAs offer a generational improvement in the fitness of the chromosomes and after many generations will create chromosomes containing the optimised variable settings [Schaffer, 1999].

Figure 10 shows an example of how a genetic algorithm works. The optimisation begins by defining the start population (set of agents). Knowledge of agents is usually presented as a character string, using a number or symbol to describe some part of problem field feature. The next step is to perform a selection or dismissal of the worst agents (survival of the fittest). The rest is combined with two genetic operations, crossbreed and mutation. The features are combined using character change as outlined in Figure 13 [Taipale and Jurva, 1999].

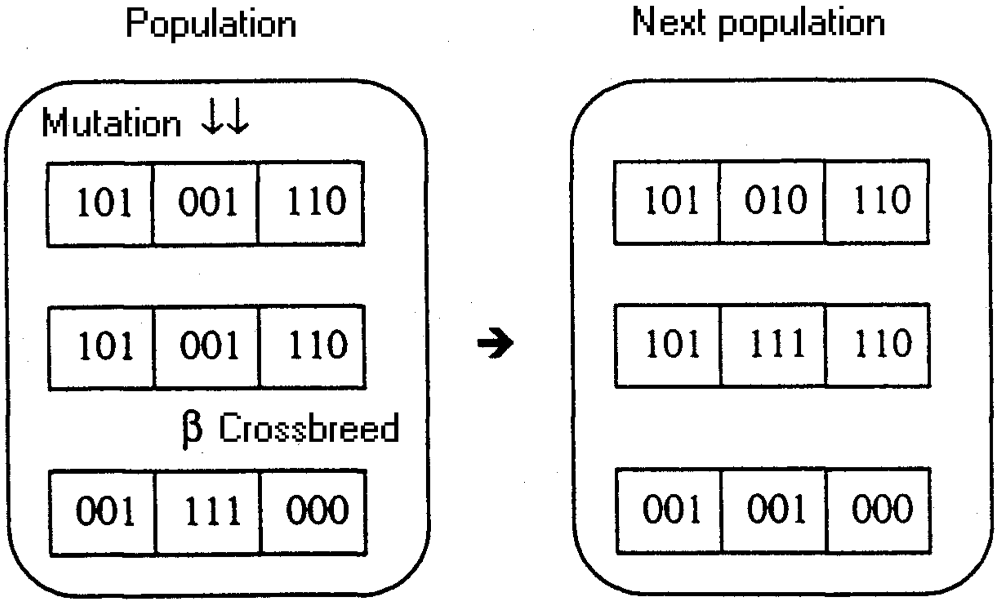


Figure 13. Example of a genetic algorithm operation [Taipale and Jurva, 1999].

Algorithms are widely researched in the field of engineering design. Some examples are hydraulic networks, satellite booms and servo motors [Bentley, 1999]. One option is to apply it to a diagnostic system design. Algorithms are sometimes used to pre-process signals, for example in neural nets, as discussed under headline 5.5.

5.4 Expert Systems

An expert system is a computer program that solves problems requiring significant human expertise. The system copies human expert reasoning and discusses with the user like a real expert [Linnainmaa, 1993]. Expert systems are used in problems where an expert can verbally describe a solution. The weak part of expert systems has been human uncertainty and inexact processing of information [Isomursu et al, 1993]. Due to this the most difficult part of expert system design is acquiring knowledge – which means that acquired from books, experts and statistics – for the system. One objective is also to separate decision mechanisms from the decision knowledge database as clearly as possible. The decision mechanism uses a knowledge database to make a solution to a given problem. An interactive user interface is also part of an expert system. With this component the user can add information to the system and get results from the system. Expertise is recorded into the knowledge base by an acquiring mechanism. Conclusions are stored in the working memory during reasoning, and the 'reason mechanism' is used to explain the conclusions. Figure 14 outlines a construct of an expert system [Linnainmaa, 1993].

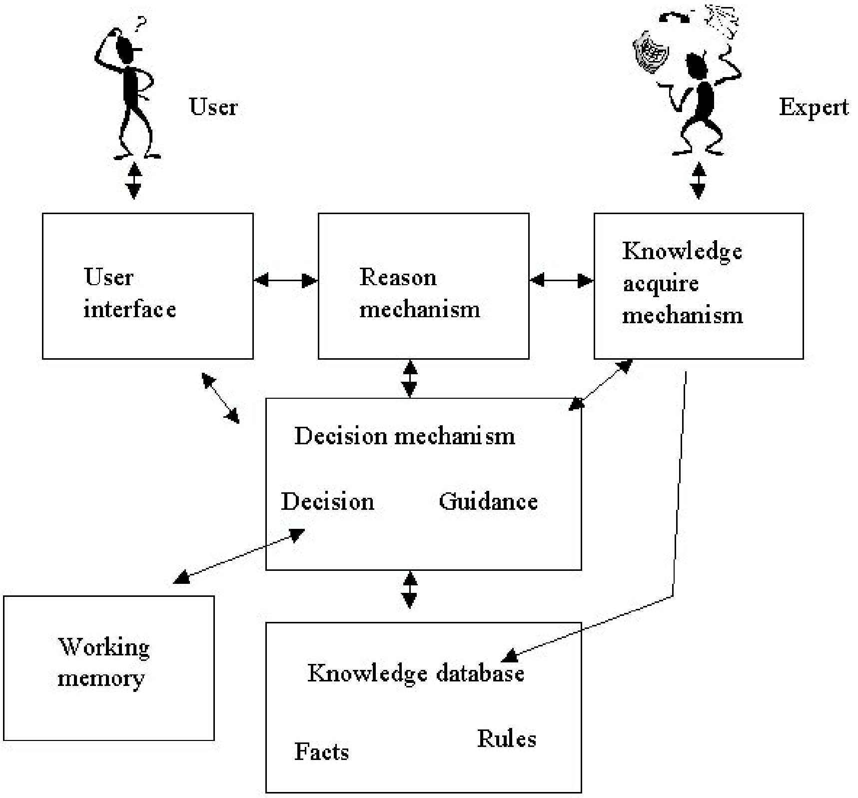


Figure 14. Construct of an expert system.

Applications of FMEA (Failure Mode and Effect Analysis) information for producing expert system decision knowledge databases have been studied [Barkai, 2000] and the improvement in performance over traditional service information tools has been encouraging.

5.5 Bayesian Networks

Bayes' theorem governs the process of logical inference - determining what degree of confidence may exist in various possible conclusions, based on the body of evidence available. This is the process of predictive reasoning. To arrive at a logically defensible prediction one must use Bayes' theorem. A Bayesian network is a causal network, i.e., a data structure that represents the dependence between associated variables and gives a concise specification of the joint probability distributions. Bayesian networks have been used in combustion engine and aircraft fault diagnostics [Isermann & Ballé, 1997].

5.6 Comparison and Hybrid Systems

Everything that is possible to do with neural nets can be done with ordinary data acquisition and analysis methods. Some solutions to given problems can be accessed much more easily with neural nets than with traditional calculation methods. It is much easier to produce neural net based algorithms than traditional calculation based algorithms, when the algorithm process is known and the input and output variables are not. The same applies when the amount of input and output is very high [Smith, 1998].

Neural nets help to solve problems where traditional computers and their applications are not at their best. Examples are interfered measurement information, adapting to environmental change and fault tolerance [Karjalainen, 1998]. These are all properties of diagnostics. Good aspects of traditional systems are fast calculation arithmetic and exact operation according to planned operation.

Often in fuzzy systems, as in traditional expert systems, the rules are based on IF-THEN type of rules. In fuzzy systems the rules do not have to be as specific as in expert systems. Neural nets do not directly handle IF-THEN types of rules; the rules are defined by weighting factors of knots, which are usually far more difficult for a human to see than IF-THEN rules. Connections between fuzzy systems and neural nets are obvious. An answer given by fuzzy rules could just as well as a value be calculated by a neuron from its inputs. On the other hand, fuzzy systems could be very close to traditional expert systems if the rules were more exact and explanatory [Isomursu et al, 1993]. The term 'hybrid system' is used when two or more of these systems are used together.

As stated earlier, wear debris morphology can be used for diagnostic purposes. Several automated systems for wear debris classification have been designed by various research organisations. These systems use machine vision and pattern recognition for classification. Expert systems, fuzzy systems and neural nets are used for reasoning [Xu et al, 1999; Reintjes et al, 2001; Sperring et al, 2001]. VTT is also active in this area [Halme, 2002].

Neural nets are often combined with other intelligent systems to build up hybrid systems. NASA and the University of Cincinnati have used genetic algorithms for input selection to monitor the health of the space shuttle's main engine. Before a network is taught, the genetic algorithm optimisation is used to diminish the amount of input information [Peck et al, 2002]. Research has also been done into the possibilities of combining fuzzy logic and neural nets [Lin et al, 1996, Zimmerman, 1996].

6 Prognostics

Prognostics means the process of predicting the future state of a system from present data. As mentioned before, this is the next step from diagnostics. Prognostics systems comprise sensors, a data acquisition system and microprocessor-based software to perform sensor fusion (MUX), analysis, and reporting/interpreting of results with little or no human intervention, in real time or near real time. Many experts expect that effective prognostics will result in reduction in failure amount and severity. Optimisation of operational performance, extrusion of the time between needed maintenance activities, and reduction of life-cycle costs may all be possible. Prognostics implementation is a challenging task for several reasons: 1) hardware and sensor technologies, 2) analytically effective prediction methods, and 3) organisational changes to capture the operational, maintenance and logistical benefits made possible by effective prognostic information. Still, the benefits to be gained by using effective prognostics appear to be higher than the cost of the task [Greizer et al, 2002a].

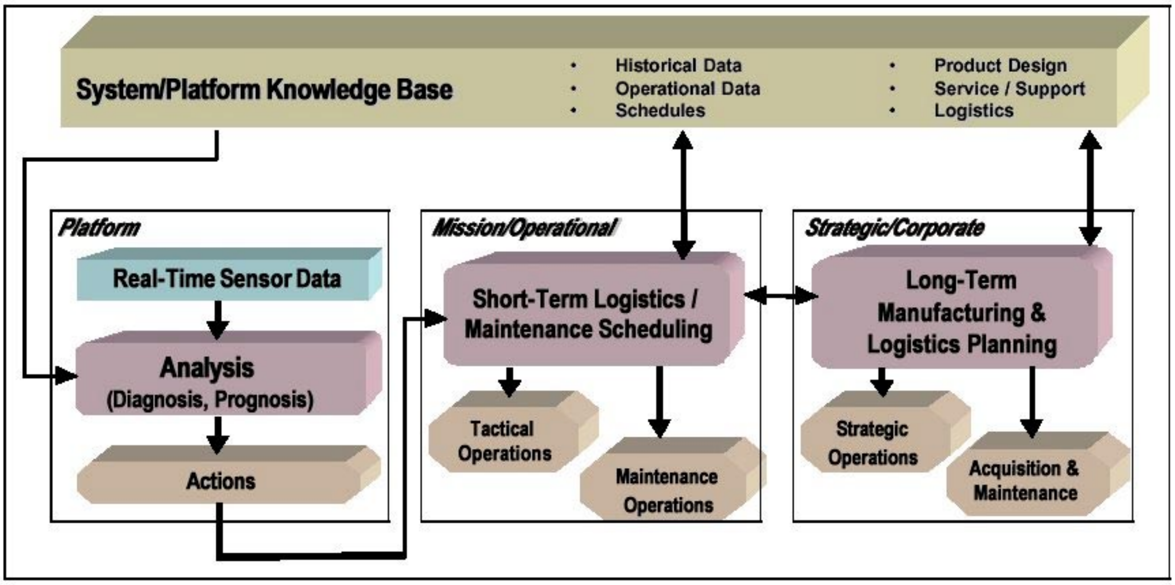


Figure 15. Logistics structures enabled by prognostics-based health monitoring [Greizer et al, 2002a].

The U.S. Army and Navy are carrying out extensive research into the use of prognostics in overall service management. Examples included the M1 Abrams tank and various naval targets [Greizer et al, 2002a, Greizer et al, 2002b]. VTT has also been active in the field of heavy machinery [Vidqvist, 2001].

7 Diagnostic System Development - AAAV

The AAAV is an amphibious tracked vehicle that incorporates a planing hull design with planing appendages, robust actuating systems, a retractable track and a diesel engine that provides 2600HP in the water and 800HP ashore. This design provides for speeds in excess of 25KTs on water and 45KTs on land. The vehicle can transition seamlessly from water to land operations by automatically transferring engine power from waterjets to vehicle tracks as needed. A typical operational concept will have AAAVs deploying from ships located over the horizon, carrying up to 18 combat-equipped Marines plus crew. The AAAVs will transit to shore where they can manoeuvre at speeds equivalent to that of the M1A2 main battle tank and with a similar operational range. [Kiley et al, 2000]

Diagnostic, prognostic and communications technologies are emerging that will enable Mission Life Prediction. MLP will allow host platform managers to adopt an asset management strategy similar to those employed in the private sector. More than maintenance, more than logistics; asset management gives the warfighter part of the basis for sound operational and tactical decisions. Asset management will enable the optimisation of assets and occasionally, when circumstances require, permit the warfighter to sub-optimise the use of his assets with full visibility of associated risk. [Kiley et al, 2000]

Smart sensors are becoming commercially available at affordable prices. This has occurred in part due to a combination of investments made by the Office of Naval Research in Condition Based Maintenance enabling technologies. These investments in both the core CBM program and several Dual Use programs have provided the private sector with funding to pursue these sensor technology development for military and commercial use. These smart sensors are expected to be no larger than 1.0 inches and they will incorporate the sensing device, signal processing, self-calibration capability, power source (either by battery or power scavenging) and the ability to communicate up line. The sensors are low weight and low power and will be much more reliable than the hardware they support. The sensors will sense whatever mechanical feature the customer requires. Typical features are vibration, fluid analysis, thermal and or acoustics. [Kiley et al, 2000]

This program will strive toward a wireless solution for all applications. The benefits of wireless technology are weight reduction and cost savings in installation and maintenance. Additionally, increased reliability is expected through use of spread spectrum, frequency-hopping technologies. [Kiley et al, 2000]

A comprehensive oil monitoring capability (TOMS or Total Oil Monitoring System) will be developed to detect debris in the lubricant as well as to determine the health of the lubricant. The intention then will be to transmit the information wirelessly within the platform. This technology will be expanded to analyse hydraulic fluid if the customer determines a requirement for that capability. TOMS will come together via a teaming arrangement involving three individual companies. A COTS oil debris monitor will be joined with a developmental oil condition monitor and the combined device will be equipped with a wireless communications capability. A key challenge inherent will be achieved a sufficient level of ruggedisation to withstand the harsh operating environment of a large diesel engine on an amphibious vehicle. [Kiley et al, 2000]

It is recognised that this objective is not trivial. Therefore a systematic approach with objectives of increasing difficulty is planned. The first objective will be to protect the diesel engine of the AAAV (valued at approximately $400,000) by providing warning of immediate, impending catastrophic failure. The second objective will be to assist in diagnosing any engine fault that is presented. The third objective will be to prognosticate a failure in some future time, based upon fluid debris and fluid chemistry. [Kiley et al, 2000]

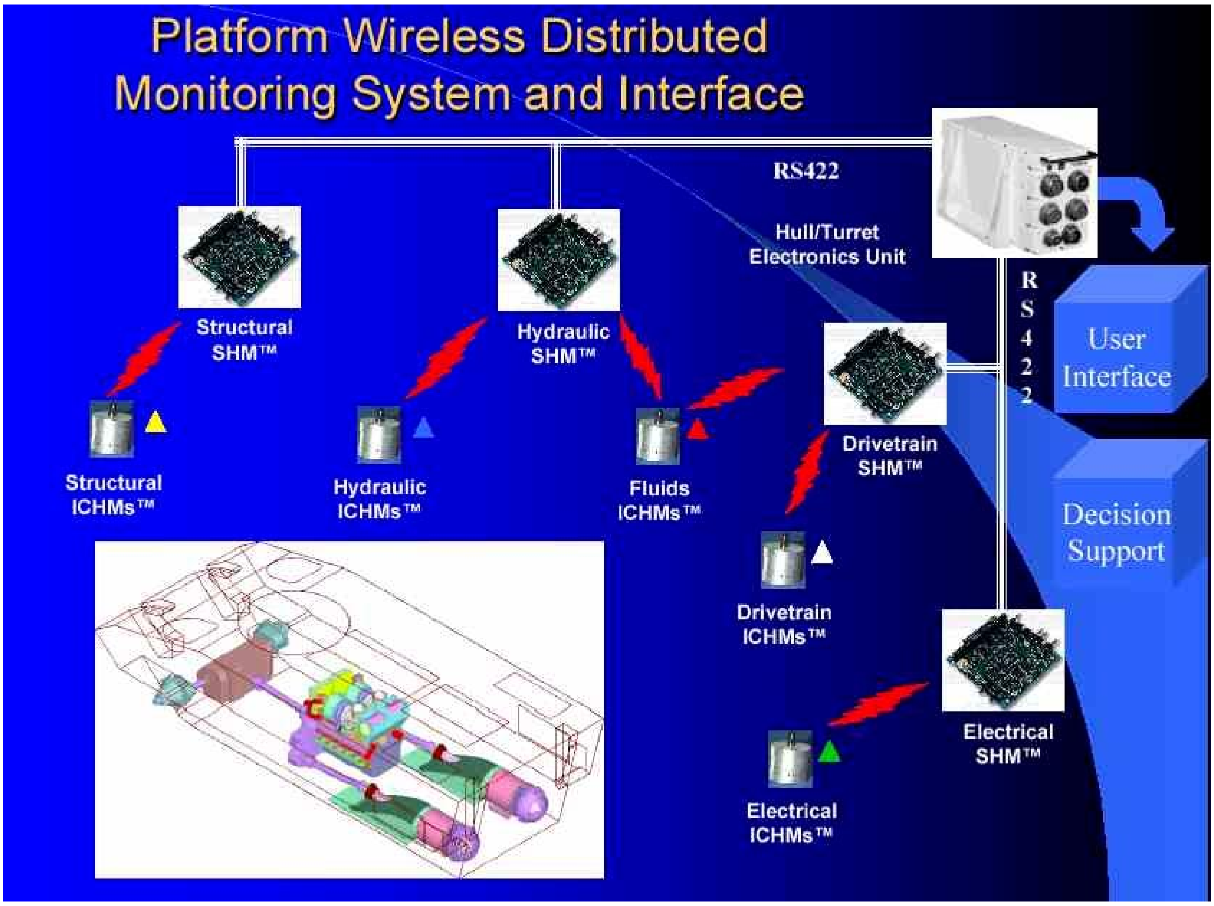


Figure 16. Wireless distributed monitoring system for AAAV [Kiley et al, 2000]

With the introduction of The Intelligent Component Health Monitor (ICHM®), Oceana Sensor offers integrated, networkable, wireless, smart sensing systems for Machinery Health Monitoring. ICHM® utilises Bluetooth™ technology for wireless data transmission and will support development of proprietary algorithms and commercial platforms. The ICHM can monitor up to 2 channels of dynamic signals such as vibration, pressure, force and acoustics using state-of-the-art 24-bit ADC as well as 4 channels of lower bandwidth data such as temperature, speed, and position. The on-board Digital Signal Processor enables the measurement of complex signals and execution of complex algorithms near real-time. Functions such as Fourier analysis, digital filtering, band level comparisons and advanced mathematical calculations can be executed locally. Data from several ICHM® nodes can be collected and analysed by the System Health Monitor (SHM™) and ultimately linked to the Internet for display in remote locations. [Kiley et al, 2000]

Selected AAAV components and systems will be outfitted with smart sensors or configured in order to capture data and information from OEM-embedded sensors. These sensors will “sense” mechanical characteristics of monitored systems. These self-calibrating sensors, or component health monitors, will process data and transmit anomalous results upline to the system monitor. The system-level monitor will in turn process data and report to the platform level monitor. Fluid and mechanical sensor data will be fused and the results subjected to a diagnostic/prognostic engine that will compute Mission Life Prediction. [Kiley et al, 2000]

A variety of diverse sensor inputs will be collected by the installed CBM system. The system is best thought of on three levels: component, system and platform. The component sensors will report to a system monitor, which will in turn report to a platform monitor. Diagnostic and prognostic algorithms will be applied at every level to eventually produce a prediction as to remaining useful life. Derivation of Mission Life Prediction will require, as a baseline, knowledge of when the system is in and out of control. Data gathering in support of this task has already begun as part of an ongoing S&T program. Initial use of this data will enable rudimentary diagnostics at the component, system and platform level. From diagnostics, and given enough operating hours from which to build a knowledge base, the MLP capability will develop. This capability will project the possibility of mission-degrading failure (on monitored equipment) over the next X hours of operation. It is recognised that this effort is likely to produce increased amounts of data and information. It is also recognised that the DoN has not always excelled in the management and use of maintenance information. In light of this reality, an initiative will be pursued under this program to ensure maintenance information products are available, in a usable format, to those organisations having cognisance over the weapons system or sub-system. Risk management strategies will be developed and implemented to address the various types of risk that must be considered [Kiley et al, 2000].

8 Summary

In this report various future trends are listed for mobile machinery diagnostics. Standards, legislation, sensors, vehicle networks, data-analysis and prognostics are discussed. Mobile machinery diagnostics are studied from two points of view: process industry condition monitoring and automotive vehicle diagnostics. Some standards for these industries are listed. Sensor discussion is mainly from an automotive point of view and vehicle networks are targeted towards wireless communication. The data-analysis part includes basics of neural networks, fuzzy systems and genetic algorithms. Bayesian networks are also into some depth. In the end an example of modern vehicle diagnostic system is presented.

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Appendix 1.

ISO 14230-3:1999 ISO
Title: Road vehicles -- Diagnostic systems -- Keyword Protocol 2000 -- Part 3: Application layer

ISO 14230-2:1999 ISO
Title: Road vehicles -- Diagnostic systems -- Keyword Protocol 2000 -- Part 2: Data link layer

ISO 14230-1:1999 ISO
Title: Road vehicles -- Diagnostic systems -- Keyword Protocol 2000 -- Part 1: Physical layer

ISO 14229:1998 ISO
Title: Road vehicles -- Diagnostic systems -- Diagnostic services specification

ISO/DIS 15031-5.2 ISO
Title: Road vehicles -- Communication between vehicle and external equipment for emissions-related diagnostics -- Part 5: Diagnostic services

ISO 9141-3:1998 ISO
Title: Road vehicles -- Diagnostic systems -- Part 3: Verification of the communication between vehicle and OBD II scan tool

ISO 14230-4:2000 ISO
Title: Road vehicles -- Diagnostic systems -- Keyword Protocol 2000 -- Part 4: Requirements for emission-related systems

ISO 7342:1982 ISO
Title: Road vehicles -- Diagnostic systems -- Equipment for ignition systems testing

ISO/DIS 15031-5.2 ISO
Title: Road vehicles -- Communication between vehicle and external equipment for emissions-related diagnostics -- Part 5: Diagnostic services

ISO/AWI 14229 ISO
Title: Road vehicles -- Diagnostic systems -- Diagnostic services specification

ISO 9141-2:1994 ISO
Title: Road vehicles -- Diagnostic systems -- Part 2: CARB requirements for interchange of digital information

ISO 9141:1989 ISO
Title: Road vehicles -- Diagnostic systems -- Requirements for interchange of digital information

ISO 8093:1985 ISO
Title: Road vehicles -- Diagnostic testing of electronic systems

ISO 7639:1985 ISO

Title: Road vehicles -- Diagnostic systems -- Graphical symbols

ISO/DIS 15031-3 ISO
Title: Road vehicles -- Communication between vehicle and external equipment for emissions-related diagnostics -- Part 3: Diagnostic connector and related electrical circuits: specifications and use

ISO/CD 15764 ISO
Title: Road vehicles -- Diagnostic systems -- Extended data link security

ISO8925 ISO
Title: Earth-moving machinery--Diagnostic ports

ISO6012 ISO
Title: Earth-moving machinery--Service instrumentation

SAE J1939-13 SAE
Title: Off-board Diagnostic Connector

SAE J1939/73 SAE
Title: Application Layer--Diagnostics

SAE J2054 SAE
Title: E/E Diagnostic Data Communications (Cancelled Jun 2001)

SAE J2190 SAE
Title: Enhanced E/E Diagnostic Test Modes

SAE J1979 SAE
Title: E/E Diagnostic Test Modes

SAE J2012 SAE
Title: Recommended Practice for Diagnostic Trouble Code Definitions

SAE J2037 SAE
Title: Off-Board Diagnostic Message Formats (Cancelled Jun 2001)

SAE J2178/1 SAE
Title: Class B Data Communication Network Messages Detailed Header Formats and Physical Address Assignments

SAE J2178/2 SAE
Title: Class B Data Communication Network Messages Part 2: Data Parameter Definitions

SAE J2178/3 SAE
Title: Class B Data Communication Network Messages Part 3 Frame IDs For Single-Byte Forms of Headers

SAE J2178/4 SAE
Title: Class B Data Communication Network Messages; Message Definitions for Three Byte Headers

SAE J1502 SAE
Title: Connections for Fluid Power and General Use Hydraulic Couplings Diagnostic

SAE J1655 SAE
Title: Predictive and Preventive Diagnostic Maintenance of Hydraulic systems

SAE J1930 SAE
Title: Electrical/Electronic Systems Diagnostic Terms, Definitions, Abbreviations and Acronyms

SAE J1962 SAE
Title: Diagnostic Connector

SAE J2205 SAE
Title: Expanded Diagnostic Protocol for OBD II Scan Tools (Cancelled Jul 1999)

SAE J1978 SAE
Title: OBD II Scan Tool

SAE J2062 SAE
Title: A Class B Serial Bus Diagnostic Protocol (Cancelled Aug 1989)

SAE J2403 SAE
Title: Medium/Heavy-Duty E/E Systems Diagnosis Nomenclature

SAE J1298 SAE
Title: Connections for Fluid Power and General Use Hydraulic Couplings Diagnostic Port Sizes and Locations

SAE J1587 SAE
Title: Electronic Data Interchange Between Microcomputer Systems in Heavy-Duty Vehicle Applications

SAE J1683 SAE
Title: MS-DOS Interface for SAE J1708 Communications

SAE J1699/2 SAE
Title: OBD-II Related SAE Specification Verification Test Procedures

SAE J1752/2 SAE
Title: Electromagnetic Compatibility Measurement Procedures for integrated Circuits Integrated Circuit Radiated Emissions Diagnostic Procedure 1 MHz to 1000 MHz, Magnetic Field Loop Probe

SAE J1939/13 SAE
Title: Off-Board Diagnostic Connector

SAE J2186 SAE
Title: E/E Data Link Security

SAE J2201 SAE
Title: Universal Interface for OBD II Scan (Cancelled Jul 1999)

DIN ISO 4092 DIN
Title: Road vehicles; diagnostic systems for Motor Vehicles, Vocabulary; identical with ISO 4092:1988 (status as of 1991)

DIN ISO 9141 DIN
Title: Road vehicle; diagnostic systems; requirements for interchange of digital information; identical with ISO 9141:1989

DIN ISO 8093 DIN
Title: Road vehicles; diagnostic testing of electronic systems; identical with ISO 8093, edition 1985

DIN ISO 7342 DIN
Title: Road vehicles; diagnostic systems; equipment for ignition systems testing

NTC 4465 ICONTEC
Title: Road Vehicles, Diagnostic Testing of Electronics Systems

Appendix 2

ISO/AWI 14830-2 ISO
Title: Condition monitoring and diagnostics of machines -- Tribology-based monitoring and diagnostics -- Part 2: Lubricant sampling

ISO/PWI 22350 ISO
Title: Condition monitoring and diagnostics of machines -- Tribology-based monitoring of machines

ISO/PWI 18436-5 ISO
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Title: Condition monitoring and diagnostics of machines using thermal imaging -- General guidelines

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ISO/CD 13372 ISO
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