# DIESEL ENGINE CONDITION AND PERFORMANCE MONITORING

BY

A. J. DAVIES, B.SC., C.ENG., C.PHYS., M.INST. P., M.B.C.S.
(*Marconi Command and Control Systems, Ltd.*)

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## ABSTRACT

Recent advances in computing techniques in fields such as simulation and artificial intelligence offer a widening scope for automation in machinery operation, control and maintenance.

The Diesel Engine Condition and Performance Monitoring and Predictive System (CPMPS) provides an on-line marine engine monitoring and management system having five main functions: assessing the condition of the engine, diagnosing faults, monitoring the engine's performance and fuel efficiency, optimizing its performance, and prediction and planning of maintenance activities.

Novel features of the design approach include the use of expert system techniques for all of these functions, including the selection of optimum sensor-sites; and also the on-line use of mathematical simulations of engine behaviour both to provide reference conditions for the condition assessment and fault diagnosis processes, and for confirmation and quantification of those diagnoses.

## Introduction

Modern-day advances in computing techniques, in fields such as simulation and artificial intelligence, coupled with the increasing capability of industry to provide compact and economic computing power and high-density memories, allow us to take a new look at what computer-based tools we can provide to the maintainer and the operator of plant and machinery.

If we examine current control and monitoring systems, the first service they provide is the regular collection and bringing together of readings from potentially large numbers of sensors—which can be permanently embedded in equipment—to a point of central monitoring, control and logging, thus removing the need for manual access and the reading and recording of visual gauges, meters, etc. Secondly, they provide fast and reliable recognition of alarm levels in those readings, and can alert the operator or perform automatic corrective or recovery actions.

We can now, however, look to the next stage of refinement, and this involves the incorporation into the computer of the knowledge and intelligence which will allow it to recognize not just *whether* a particular piece of equipment is working, but *how well* it is working. This would allow us to monitor—and therefore to improve—the efficiency of the equipment; and also to identify and quantify its deterioration, so as to plan for effective maintenance, and to predict and avoid many of the failures which are now detected only retrospectively by the alarm systems.

The Diesel Engine Condition and Performance Monitoring and Prediction System (CPMPS) project was established to develop an on-line marine engine monitoring and management system having five main functions: a continuous assessment of the condition of the engine; the diagnosing of faults and out-of-tolerance conditions; monitoring of the engine's performance and fuel efficiency; the optimization of its performance; and the prediction and planning of maintenance activities.

In the CPMPS system, a relatively small number of strategically-placed sensors gathers data from the engine throughout its combustion cycle, and these are used to assess its condition and performance. Advice can then be presented to the operator for optimizing operating settings, maximizing fuel efficiency, the correction of faults, and the scheduling of maintenance activities.

Novel features of the design approach include the use of expert system techniques for all of the above functions, including the predetermination of the sensor-sites; and also the on-line use of mathematical simulations of engine behaviour both to provide reference conditions for the condition assessment and fault diagnosis processes, and for confirmation and quantification of those diagnoses.

## The CPMPS Project

The CPMPS project is a programme sponsored by the U.K. Department of Trade and Industry, and designed to investigate the practicability of using advanced techniques in the fields of simulation and artificial intelligence to implement a performance and condition monitoring equipment for marine diesel engines. The work has been carried out over the last three years by a consortium consisting of Lloyd's Register of Shipping, the Marconi Company, and the marine engineering departments of the University of Newcastle-upon-Tyne and Humberside College of Higher Education, with support from a committee of ship owners represented by Shell International Marine, and other universities and consulting agencies.

This article reports on the experiences of the project to date, and shows how the different elements of the design have been integrated into a prototype on-line implementation.

## Performance and Condition Monitoring

It is necessary at the outset to draw a distinction between Status Monitoring and Alarm equipments, and Performance and Condition Monitoring equipments. The former types of system are well established and meet strict standards for safety and availability. The purpose of such systems is to detect failures as quickly as possible, and to protect the vessel and crew from loss or damage which would be the consequence of such failures, or of continued operation in such circumstances. They must be simple, safe and unequivocal.

However, an engine alarm generated by the failure of a component will have come too late to prevent the possibly considerable cost of a long period of inefficient engine operation due to its running with a degraded component, or to its gradual pre-failure deterioration. It will also undoubtedly occur at a time when recovery and repair is least convenient and most costly. Furthermore, it may give no indication at all for certain engine conditions which may be caused by combinations of degraded but not actually failed components.

What is required in these cases is a system which will provide an ongoing assessment of the condition of the engine, and of its performance under different operating conditions, so that its operation can be optimized at all times, fault conditions can be predicted early on, and effective maintenance activities can be planned well in advance.

The aims of the system envisaged by the CPMPS project are to:

(*a*) Reduce or remove the cost of unpredicted and unexpected failures.

(*b*) Improve engine availability and reliability.

(*c*) Optimize the operation of the engine.

(*d*) Enable effective maintenance and repair planning.

The achievement of these aims will lead to:

(*a*) Reduced running costs and improved fuel economy.

(*b*) Reduced maintenance and repair costs.

(*c*) Better utilization of engineering personnel.

The means by which the system seeks to achieve these aims are by firstly measuring the performance of the engine using information based on the online monitoring of selected parameters, and then deriving an assessment of the condition of the engine, and attempting to diagnose the existence and severity of specific component conditions.

## Project Approach

From the outset the aim of the project was to derive the knowledge base for the expert system which assesses the engine's condition from actual data obtained from the engine, and to use heuristic knowledge to refine and set into context rather than as the central basis for knowledge. Similarly, the engine simulations used during development and in the online system have been refined by comparison with, and calibrated against, the actual measured performance of the engine.

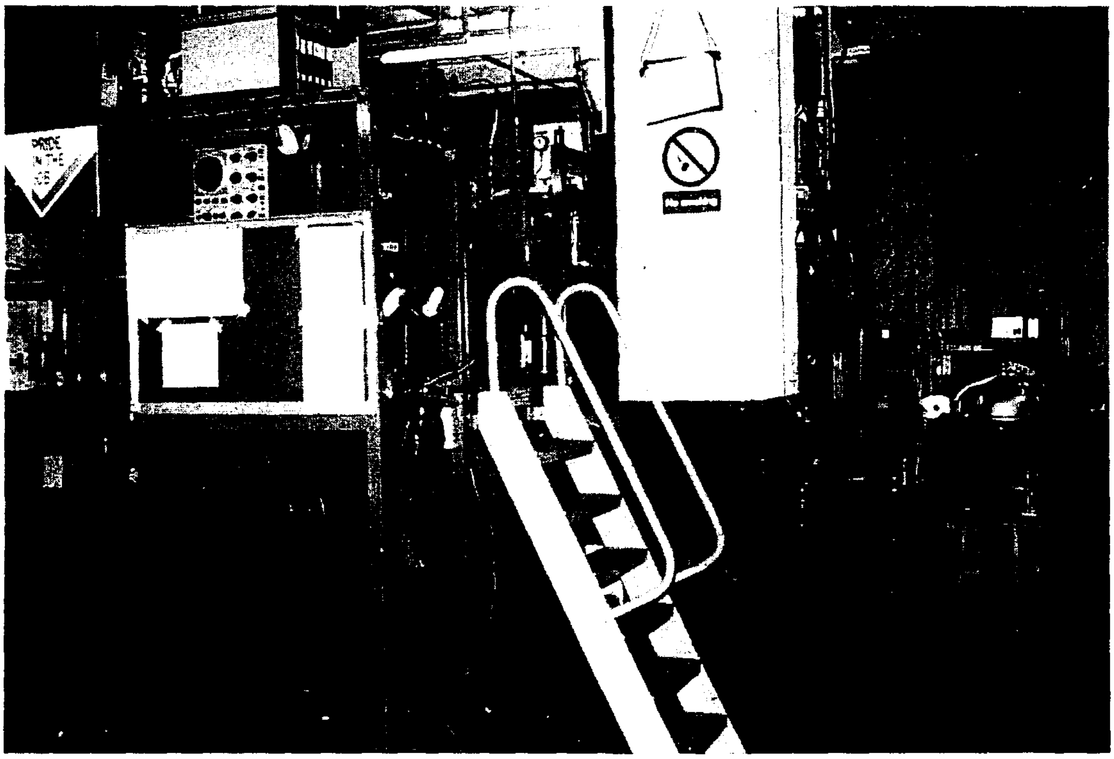

FIG. 1—THE RUSTON 600 APC ENGINE TEST RIG AT NEWCASTLE

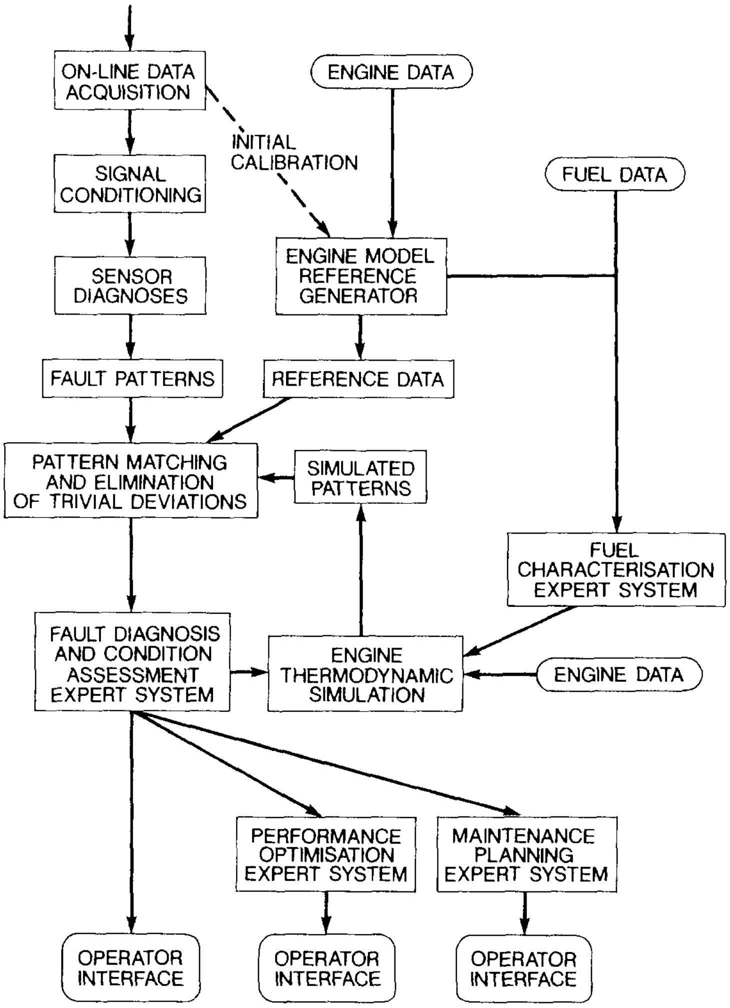

FIG. 2—CPMPS SYSTEM

Information recorded by Lloyd's Register regarding the main failure modes of about 2,500 slow and medium speed engines built and operated during the period 1970–1981 were studied, and from this information a total of 80 faults and fault conditions were selected for inclusion in the investigation. A 750 rev/min 6-cylinder marine diesel engine at the Newcastle site was chosen as the testbed, (FIG. 1) and this was instrumented with about 200 sensors and measuring devices.

The first stage of the project involved many hundreds of hours of engine testing and data collection. At first the engine was completely overhauled and run in 'reference condition', to calibrate the simulations, and set the reference patterns for later deviation analysis. Subsequently, a predefined series of faults were introduced, for example by machining measured defects into various components to simulate wear or distortion, and measuring the performance of the engine via the sensor readings in each case. Some 300,000 readings were recorded for each 'sample' run.

Because of the large amount of data collected, automatic means of processing the data were used on the development computers, resulting in the selection of a minimum set of 'useful' sensors, the derivation of a characteristic pattern of sensor readings for each fault, a set of rules for recognizing and discriminating between each of the faults, and values for the natural variability and sensitivity of each of the sensors.

This information was then used to provide the information source and rule base for the fault diagnosis expert system. This forms the hub of the CPMPS system, as shown in FIG. 2. Each of the individual processes in the system was tested off-line by replaying into them the recorded measurements from the engine trials. Finally, each of the sub-systems was integrated together onto a single computer system and tested on-line by attaching 'live' to the engine and running diagnoses and assessments in real time.

A summary of the development approach is shown in FIG. 3.

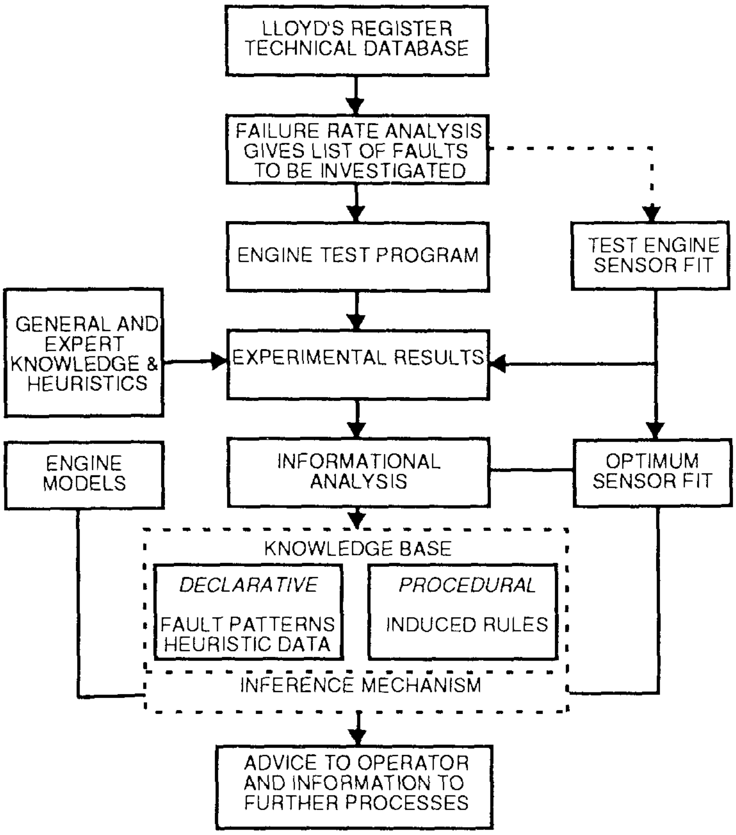

FIG. 3—CPMPS PROJECT APPROACH

## Selection of Sensors

The selection of sensors and their siting in the system are based on a number of considerations, which may be summarized as:

(*a*) The minimum number of sensors should be chosen that allows the maximum level of fault diagnosis. To show what we mean by this, let us look at the simple example shown in FIG. 4. Here there are three faults which altogether affect a total of ten sensors, each of which can read 'good' or 'bad'. However, we only actually need to look at sensors 2 and 3, since we can detect all the faults by looking at the indications of 2 and 3, and we can discriminate between the faults by looking at the combination of 2 and 3. Of course the real system is looking at 80 faults and 200 sensors, and can use each of the seven possible conditions of each sensor as well, so that the determination of the minimum set is quite complex.

(*b*) All sensors should be as non-intrusive as possible, both to remove the cost of adaptation of engine components for sensor fitment, and to eliminate the possibility of degradation of component performance or reliability by such adaptation.

(*c*) Sensors should be used which are as inexpensive as possible whilst retaining adequate performance and reliability in their working environment.

The final placement of sensors in the system was done partly by reference to expert knowledge, and using statistical information obtained from the records of Lloyds's Register of Shipping; but was mainly the product of the Rule Induction process. Rule Induction is a process which establishes descriptions of a number of known situations (in this case engine 'fault' conditions), and examines the evidence which accompanies each one. It then attempts to derive a (minimum) set of rules by which the situation could have been deduced from the relevant evidence in each case. These rules can then be used to process new sets of evidence as they are collected online.

During the initial testing phase of the product engines at the two testing sites were instrumented with a total of more than 200 sensor points, some of which were manually observed, but most of which were recorded automatically by computer. Readings were taken from all the sensors at each operating point of the engine, and at each induced fault condition. Subsequently—offline—rule induction techniques were applied on the data accumulated to identify which set of sensor readings were significant in each of the tests, and in particular which subset of those readings was necessary to distinguish between the diagnoses of each of the faults.

FIG. 4—SENSOR SELECTION

| FAULT CONDITION | SENSORS AFFECTED | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| **NO FAULT** | | | | | | | | | | |
| FAULT #1 | √ | √ | √ | √ | √ | | | | | |
| FAULT #2 | | √ | | √ | | | | √ | √ | √ |
| FAULT #3 | | | √ | √ | | √ | √ | | | |

There is also a need, however, to provide a certain amount of redundancy in sensor siting, so as to give some degree of corroboration of each sensor reading by alternative indications or by nearby effects, especially where sensors are particularly critical, or may be particularly prone to failure or damage due to difficult operational sites or less robust technology. In the event, a total of some 26 sensors were selected as being 'diagnostic', although about 100 were monitored in the final system, as providing useful or corroboratory evidence either to the diagnostic system or simply as a direct display to the operator to provide extra confidence in the diagnosis.

The majority of the sensors used in the system are thermocouples, or piezoelectric or strain gauge pressure transducers, although the effects of more sophisticated measurements such as fuel abrasivity and wear debris content have also been considered. One of the most useful measurements, however, is to record the pressure readings in the cylinder throughout the combustion cycle (synchronizing the readings to increments of the crankshaft angle). During the experiments, these measurements were made using pressure transducers embedded in the firing cylinder (connected to high-speed analogue-to-digital data acquisition circuitry). However, results obtained from transducers mounted non-intrusively (on the indicator cocks) have been shown to compare favourably with these readings and would almost certainly be used rather than embedded sensors in a commercial installation.

A number of mathematical techniques[1] are used in the processing of the readings taken from the sensors to ensure their integrity, and to facilitate the identification and diagnosis of possible sensor faults, so that the associated readings can be eliminated from the subsequent engine assessment and diagnosis processes.

## Signal Conditioning

In the data acquisition phase of the CPMPS cycle we distinguish between two types of data. 'Steady State' data refer to measurements which, once the engine has attained a particular steady operational state, remain relatively steady themselves, at least throughout the combustion cycle. 'High Speed' data are those which vary through the combustion cycle, such as the in-cylinder pressure. This latter data has to be captured and recorded by the computer at high speed (in this case, at every half-degree through the cycle). However, we are actually looking for specific items of information within the data (such as the point of maximum pressure), so that the system has to extract this information and pass it on to the diagnosis task and to the fuel assessment system.

Each item of information, either extracted from the high-speed stream, or taken as an individual reading from the steady-state sensors, has a variation associated with it, and the system calculates Maximum, Minimum, Average and Standard Deviation for each. Excess variability in a reading may itself be a problem indicator (this information also proves useful for sensor diagnosis).

## Condition Assessment and Fault Diagnosis

One of the main advantages of the 'human' approach to situation assessment is the flexibility with which a number of different techniques and areas of knowledge can be brought to bear to arrive at a final judgement. Several Artificial Intelligence techniques which attempt to take advantage of this type of approach have been applied in this system.

The development tool used for the production of the system ('MUSE') provides a 'Blackboard Architecture'. In this type of architecture, a problem is considered by a number of different 'knowledge sources', each of which contain knowledge about particular aspects of the problem, or about particular behavioural rules or situations, etc. Hypotheses or partial solutions are built up on the 'blackboard' as each knowledge source makes its contribution. Each knowledge source monitors the development of the solution, and will act if it can contribute at any stage to further refinement.

Mixed mode reasoning is used in the rule bases; that is to say, forward and/or backward chaining can be applied as appropriate to developing a solution. In simple terms, a forward chaining process attempts to follow each set of consequences through to an end-point, which becomes its conclusion. Backward chaining sets up a hypothesis, and tests to see whether the conditions necessary to support that hypothesis are present, in which case it adopts the hypothesis as its conclusion, or part of its conclusion (or it may try another hypothesis).

The main types of knowledge which are invested in the system are in terms of fault pattern matching, and causal knowledge. Causal knowledge is the qualitative representation of physical, empirical and heuristic rules, which are used mostly in this system for confirmatory purposes.

The main means of extracting information for contributing to the stored knowledge was to use rule induction techniques on the experimental results as the basis for pattern definition and for generating matching rules. The aim of this approach was to establish and assess a means of automatically generating the knowledge base which can be used when installing the system on new and different types of engines. In practice, the output of the process still required some degree of expert refinement and qualification.

The test engines were run at several load/speed points firstly in a reference condition (immediately after overhaul) and then a large number of times having in each case one or more faults introduced, with varying degrees of severity. In each instance sets of all the sensor readings were taken for analysis.

Each of the sensor readings was normalized and expressed in numerical but qualitative terms (0 to 3 representing normal up to high deviation, +ve for high, −ve for low). Natural variability and sensor accuracy both, of course, need to be taken into account. In this way a 'deviation pattern' was described for each fault. Also, from this information, sensors could be graded according to their usefulness in different circumstances: as being not reactive at all to faults, or not reactive in a predictable or consistent way; as being very useful in detecting faulty conditions but not useful in discriminating between faults; or as being diagnostic of particular faults.

The basis of the fault diagnosis is the matching of the reading patterns derived from measurements taken during on-line operation in real time, against the deviation patterns stored from the above exercise. Subsequent estimation of condition is based on the patterns matched, the closeness of fit, and information from other knowledge sources which may be relevant.

It should be noted at this stage that the patterns upon which the condition diagnoses are based in the present system represent steady-state engine operation: that is to say, the effects of transient behaviour during manoeuvring, load changing, etc., are not being considered at stage. During on-line operation, therefore, the system will not attempt to diagnose while transient operation is detected. However, unlike the status monitoring equipments mentioned earlier which must of course continue to operate at all times and under all conditions, condition monitoring need not be performed continuously, and there should be no problem in waiting for a suitable period of steady operation before performing the next assessment.

## The Role of Simulation

Simulation is used in the system, in broad terms, to provide interpolation between the fixed points of knowledge. This is necessary in two areas.

Firstly, since the deviation patterns are to be compared with the reading patterns for the engine in reference condition, we need to know what the reference readings should be for the engine at the precise operating point at which the on-line readings have been taken. The experimental reference points (as described above) can only practically be taken at a small number of operating points. These points, therefore, are used to calibrate a model of the engine, and the readings for any point in the operating space of the engine can be generated by the model.

Since we are dealing here with a 'reference' engine, the model needs only to represent a single behaviour, and we choose, for speed and efficiency reasons, to describe it mathematically via a 'black box' model (using a polynomial). This gives a fast process which is also relatively easy to calibrate on-line, for example after a major maintenance or overhaul of the engine.

The other requirement for simulation in the system arises because the stored fault patterns represent a finite set of fault conditions, and precise matches are unlikely. Given a sufficiently accurate and flexible simulation, a fault hypothesis can be fed into it at given engine conditions, and it can predict a set of reading deviations which can then be matched against the measured set, to confirm or quantify the diagnosis. It can also be used to test for multiple-fault hypothesis; or to predict the behaviour of the engine at proposed operating points, with proposed fuels, or with supposed further degradation of components.

A simplified version of a thermodynamic simulation program has been adapted for the CPMPS system, allowing for online operation. Even this version is quite slow; but timescales of several minutes should not be prohibitive in this area of the system's functionality.

## Fuel Effects

Since the combustion performance of the engine is to be used in assessing its condition, then the effects on combustion of the particular type and quantity of fuel which is in use has to be taken into account.

In practice, different levels of information about those parameters of the fuel which affect its combustion properties might be available in different circumstances. The results of an on-shore laboratory analysis of the fuel are often obtained before a particular fuel is routed to the engine; the Chief Engineer may use an on-board 'test kit' to yield some basic fuel properties; or, as a minimum, the density and viscosity of the fuel can be estimated from information on the bunker delivery ticket.

In order to obtain an assessment of fuel ignition/combustion characteristics, particularly when based on such variable or incomplete information, an expert system has been developed[2]. This system is based on a Fuel Information Knowledge Base built up from expert knowledge, chemical and statistical analysis, and Rule Induction based on a large number of tests. The system will estimate, for a given set of fuel properties, a predicted range of combustion Effect Parameters, as well as producing a broad characterization of the fuel, both in the form of a report to the operator and as an output to the predictive maintenance system (which will assess the effects of the particular fuel on the ageing rates of the engine components).

A set of measured Combustion Effect Parameters can be obtained from the results of the online monitoring of the engine (via heat release calculations based on the cylinder pressure diagram and ignition delay.) These actual parameters are compared with the calculated parameters. Any discrepancy between the sets may be the result of an engine fault. Engine simulations run using both the predicted and calculated Combustion Effect Parameters will therefore be compared with the actual engine readings, and the results passed on to the Fault Diagnosis expert system to determine which set of parameters should be used to give the highest degree of confidence in assessing both the state of the fuel and of the engine.

## Performance Optimization

The function of the performance optimization system is to provide advice on the optimal settings, given the assessed engine condition and fuel quality. It takes the form of an expert system which is being developed with the aim of minimizing fuel consumption and maximizing engine maintenance periods. In any given installation the options which can be taken under consideration will be limited by the adjustments which are actually available on the particular engine. On current installations these may include such parameters as charge air temperature, varying injection timing, varying injection flow rate, and variable geometry turbocharging.

## Maintenance Planning

Maintenance activities generally can be classified in a number of ways, but fall broadly into those activities which are based on fixed or arbitrary maintenance schedules, and those which are reactive to the condition of the engine and its components. Cost savings can be achieved by adopting maintenance plans which are based on the measured or assessed condition of the engine, as demonstrated by Hind[3] and others. This approach can also result in more efficient use of manpower, reductions in spares holdings, and increased engine availability and operating life.

Reactive maintenance planning is a complex subject with potentially a very large number of variable inputs. The baseline inputs are the planned or reference maintenance schedules for the engine components and sub-systems, and the Manufacturer's recommended maintenance periods, which will have been based on theoretical wear rates. These requirements will be modified by the effects of parameters which are being continuously assessed by the Condition Monitoring system, in particular operation in faulty or 'off spec' engine conditions, and operation with different qualities of fuel. Other dynamic effects which can potentially be monitored or manually input include operation in heavy weather conditions, and manual intervention for interim refurbishment.

Based on these parameters it is the aim of the Maintenance Planning expert system to produce short term (day-to-day), medium term (planned in-port maintenance), and long term (e.g. Five-year) maintenance plans, which take into account statutory and Classification requirements.

In order to assess the short and medium term requirements, knowledge must be built into the system as to what activities can be done at sea and which must be done in port. In the case of a major engine condition degradation the alternative may present itself of continuing the voyage with the engine in its degraded state; or of stopping the engines for repair and then continuing with the engine in an improved state. The system will be capable of providing predictions of the performance in the degraded state and in the potential repaired state, allowing the appropriate choices to be made. In practice, the decision would have to take into account not only factors such as the length of the voyage, and the level of facilities available at the next port, but also financial factors (such as late delivery penalties), weather forecasts, etc.

As the knowledge base is expanded to take into account more of these factors, advice of increasing quality can be presented to the ship's officers charged with making the ultimate decisions.

## Operator Interface

One of the features of any expert system should be that it does not merely report a conclusion or hypothesis to the user, but is also able and prepared to justify its deductions. It must therefore record the route through which its logic passes, whether forward or backward chaining, so as to present, or to have available for presentation on request, the reasons for its choices at each decision point. In the general case this gives the operator greater confidence in the advice given, but it also allows the more experienced operator to question the system in the event that he is doubtful about the conclusions reached by it. He can, for example, force the system to temporarily ignore a sensor reading which he feels is doubtful but upon which the system has based a pivotal decision, so as to view what alternative conclusion might have been reached.

Whilst a textual format is appropriate for this kind of interaction between the system and the operator, it was considered that the general situation display for the operator should be a relatively simple colour mimic picture. The one currently used shows the major sub-systems of the engines 'blocks' on the display, one or more of which will change colour and show 'FAULT' when a fault is diagnosed in that sub-system. 'Selecting' the block brings up a diagrammatic representation of the sub-system, showing each of the sensors as having a 'good', 'suspect' or 'failed' reading. Further information on each sensor (name, location, current reading) can then be summoned as required.

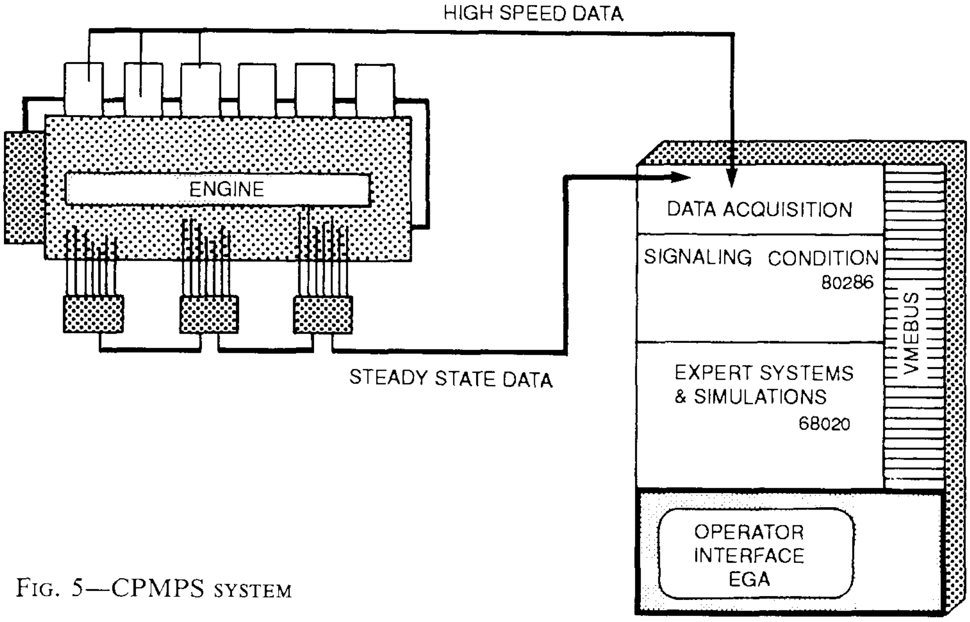

Fig. 5—CPMPS system

Fig. 6—The CPMPS operator workstation in development

## The Integrated System

Although the first test phase has involved the use of the shore-based engine at Newcastle, it is the intention to move on to sea trials very shortly afterwards. Therefore, whilst the development system used various workstations, DEC VAX Computers and Personal computers, the run time system built up for the trials was chosen so as to reflect what might be a realistic configuration and physical format suitable for onship operation.

FIG. 5 shows the on-line system configuration. The expert systems, which were all developed (FIG. 6) on a Sun Workstation, were ported onto a Motorola 68020-based processor system running on VME-bus. The simulator modules are also hosted on this processor. In order to perform the data acquisition, the operator interfacing, and most of the signal conditioning, an IBM PC-compatible 80286 processor board with Enhanced Graphics Adapter was added to the bus, sharing memory with the 68020.

The steady-state data is acquired using a Schlumberger system of serially-networked measurement pods (IMPs), which are mounted on the engine gantry and connected to the sensors. Each IMP is sealed and has high vibration and shock resistance. High-speed sensors are connected directly to analogue-to-digital converter boards also mounted on the VMEbus.

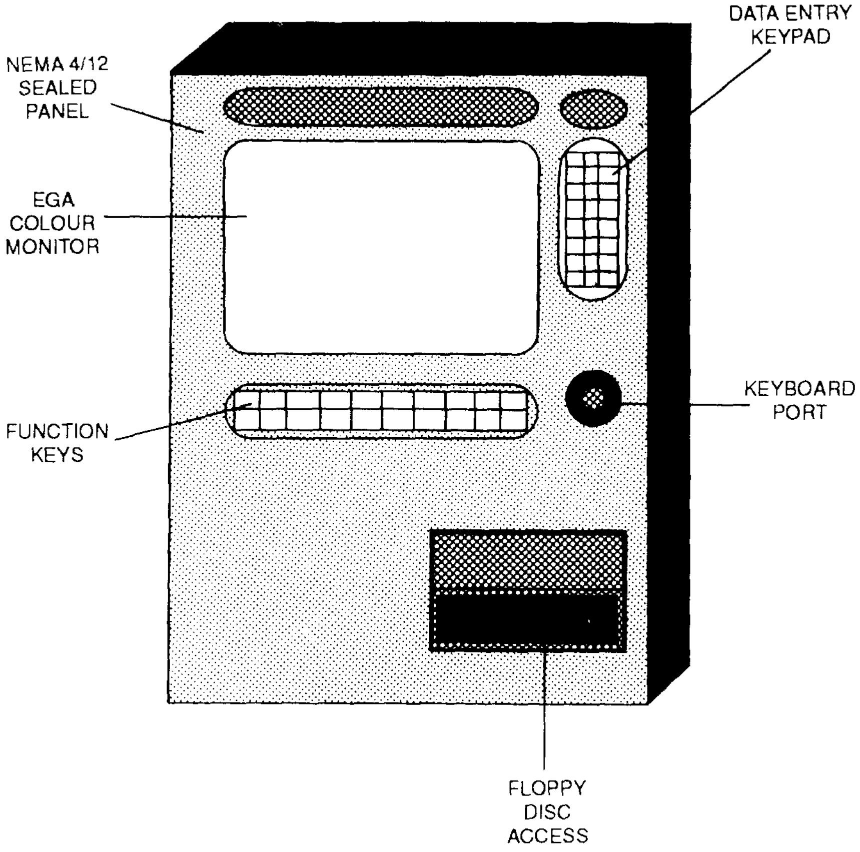

FIG. 7—CPMPS OPERATOR WORKSTATION

In order to mount the processors, and also to provide a suitable operator input and display capability, an industrial workstation was chosen, as illustrated in FIG. 7. This unit has a sealed front panel, and also has a high shock and vibration specification. A shock-mounted removable disk allows engine data to be recorded regularly and removed for offline analysis. Operator input is via a sealed membrane keyboard.

## Summary and Conclusions

The project has established the on-line use of expert of expert system techniques, in conjunction with on-line engine simulations, to provide a means of continuously assessing the performance and condition of a marine diesel engine. Data to provide the knowledge bases has been derived using largely automatic means from experimental results. These relate to measurements of the engine's performance under various induced conditions, and the effect on the combustion characteristics of different types and quality of fuel. It has also been shown that the various functional sub-systems can be adapted and integrated together into a processing unit of a size and type suitable for commercial 'on board' use.

Further work on the system will investigate the degree of adaptation necessary to 'customize' it onto any other type of diesel engine, and the level of automation which can be introduced into this process. A series of trials of the unit in a shipborne environment are also expected.

## Acknowledgements

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