DESIGN OF AN INTELLIGENT SUPERVISOR OF A SHIP ENGINE ROOM

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Abstract This paper presents the prototype of a knowledge based supervisor for a turbo - charger system of the main engine of a ship. The knowledge representation is based on qualitative models and uses Propagation of perturbations and Qualitative Simulation as reasoning techniques. Qualitative models of the main parts and some illustrative examples showing different time-scale processes are given.

Keywords: Qualitative modelling, causal propagation, supervision, engine monitoring.

INTRODUCTION

The application of knowledge based techniques in ship engine control rooms is a field of increasing interest because of the following factors: a) the complexity of the installations, b) the singular onboard working situation, c) The economic benefits of any improvements of the performance of the installations and e) the ever decreasing number of maintenance and supervision personnel. During the last few years a number of comercial systems and rule based prototypes such as IAES (Katsoulakos et al. 1989) dedicated to supervision and diagnosis have been developed.

Any knowledge based system needs to solve two crucial aspects: the representation of the knowledge and the manipulation of the knowledge, (reasoning) in order to fulfill determined objectives. There are different techniques to represent and manipulate the knowledge involved in the domain of a specific application. From the representation point of view, rules, predicates, objects or frames and other more complex entities, such as models, can be mentioned. From the knowledge manipulation point of view, forward and backward reasoning, propagation and simulation can be mentioned as the most used techniques.

One of the most useful fields of application of expert systems is intelligent monitoring of complex processes. Intelligent monitors are supposed to assist control center operators by performing, among other things, the following functions: Presenting relevant information about the present state of the process to the operator. Diagnosing faults, if any, that lead the process to its present state. Predicting possible future states or faults if certain actions are (are not) taken. Giving advice about possible actions to be taken.

All these functions need analysis and interpretation of sensor data to determine their meaning in order to explain what is (or may be) taking place in the process. It is clear that this type of interpretation must be based on a profound knowledge of the process. This must comprise not only knowledge of the separate parts, but also of how they are connected and about how they work together.

Object-oriented programming languages are good tools for representing this type of knowledge. Concepts of parts, components and their relationships are easily coded in these types of languages. On the other hand, Qualitative Simulation (Kuipers,1986) seems to be the appropiate technique to perform the causal reasoning needed in some of the functions mentioned above.

This paper presents the prototype of a knowledge based supervisor for a turbo - charger system of the main engine of a ship. The knowledge representation is based on qualitative models and uses the propagation of perturbations and Qualitative Simulation as reasoning techniques. Artificial Intelligence Techniques have been applied to ship engine monitoring in the past (Katsoulakos et al., 1989), although the approach used was *rule based* and did not consider qualitative behaviour. The main objective of this work is to develop qualitative behaviour models of the main engine a ship that could be used for monitoring, failure detection, diagnosis, prediction and instruction.

Here we consider a system as a collection of interconnected components. So the behaviour of the system is obtained from the behaviour ef each component and the connections between them. This is component based ontology, but each component is modelled following Kuipers' (1984) interpretation. The models are based on variables which are linked between themselves by several types of constraints.

The reasoning is done by using the Qualitative Simulation (QSIM) algorithm proposed by Kuipers (1986). The result of Qualitative Simulation is a description of the possibles qualitative states the system can reach in its evolution from an initial state.

In the quasic-static processes we apply qualitative propagation of disturbances through the constraints. The possible ambiguities in the tendency of any vari-

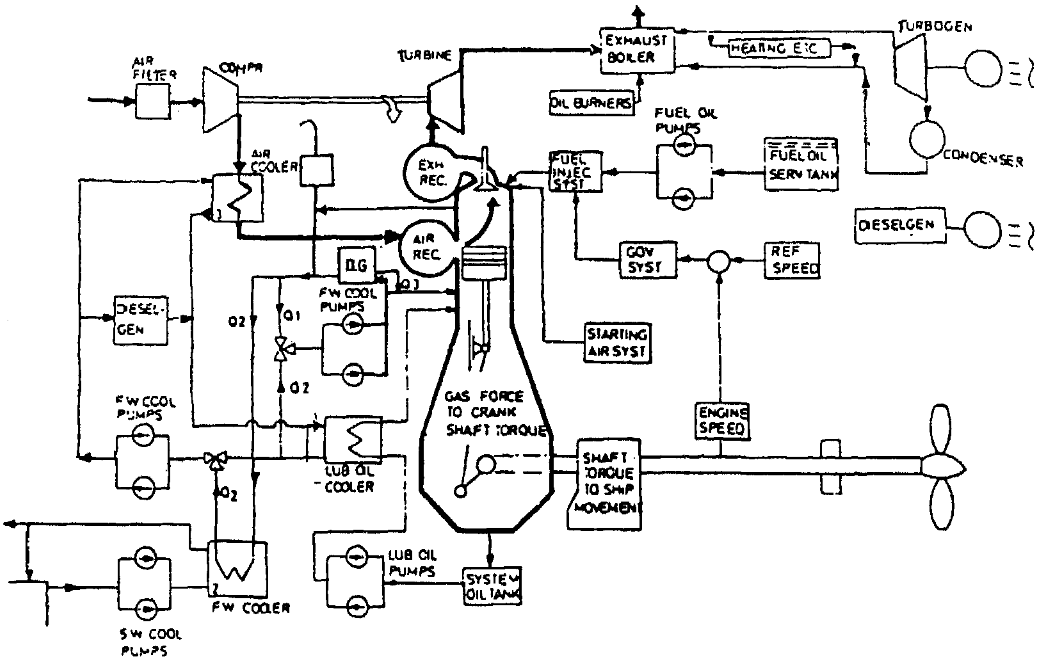

Figure 1: Ship main engine turbocharger system

able are reduced by the use of heuristic rules, causal constraints, (De Kleer 1984, Oyeleye and Kramer, 1990).

The system developed has been implemented in *SMALLTALK* (Goldberg and Robson,1984), which is a general purpose object-oriented language and thus allows Qualitative Simulation and time causal reasoning to be integrated into a more general reasoning system.

The paper is organized as follows. Section 2 describes the process concerned and the model developed while section 3 is dedicated to presenting the supervisor structure. Some simulation runs showing malfunction detection are presented in section 4. Section 5 is dedicated to presenting some concluding remarks.

MODEL DESCRIPTION

The engine room of a ship considered is composed of the following subsystems: The main engine, the main engine turbocharger, the auxiliary engine, the lubricating subsystem, the sea water system, the combustion feeding system, the compressed air system etc.. The engine room of a ship is a fundamental part of the same and has, therefore, to be continuously supervised.

The process considered, see figure 1, corresponds to a ship main engine turbocharger system. Naturally aspirated engines draw air of the same density as the ambient atmosphere and this density determines the maximum weight of fuel that can be burned in the cylinders and therefore the maximum power obtained. If the air density is increased, by a compressor, the amount of air is increased and more weight of fuel can be effectively burned and the power developed also increases. This procedure is implemented in most modern diesel engines by using exhaust gas turbocharging where exhaust gases are used to power the compressor. A substancial amount of the total heat energy is wasted to the exhaust gases, and although it is relatively inexpensive to drive the compressor directly from the engine by gear, an increase in power is obtained by using the exhaust gases to drive the compressor.

The inlet air is filtered and goes through the compressor. As the temperature of the inlet air after being compressed is too high to go into the cylinders, it has to be cooled down. This is accomplished by an air cooler using sea water as a coolant. Some of the surplus energy of the exhaust gases is used to power the turbine coupled with the compressor as indicated before.

Temperatures of gases in ship diesel engines are very valuable sources information for monitoring their conditions. A model of the behaviour of the gases was considered to be a good tool for the supervision of ship engine rooms. In this sense, a qualitative model of the turbocharger subsystem was developed. A modular and hierarchical decomposition of the system was established. This way of representing the system adapts to physical reality, topology, the operator's mental models and allows for easy generalization when representing the global complexity of a ship engine room.

The main variables taken into account by the model are: cylinder inlet air pressure and temperature, air-cooler inlet air temperature and pressure drop, sea-water inlet temperature, turbine and compressor temperatures and exhaust pressure and temperatures.

All these components have been modelled according to Kuipers (1984) although the idea used for their aggregation in order to form the the ***system*** is nearer to the component ontology used by De Kleer (1984) as mentioned before. The same applies to the concepts of connections, causality and heuristics used.

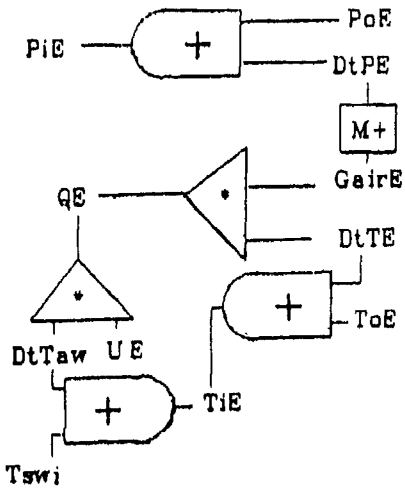

Fig 2. Cooler Model

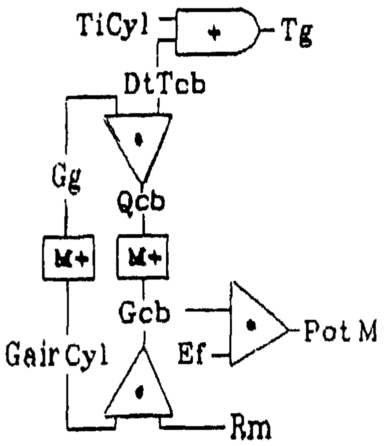

Fig. 3 Cylinder Model

The models have been obtained using physical laws and heuristic rules, given by the experts. The heuristic rules are used to resolve the ambiguities originated in the Qualitative Simulation. Two type of models, corresponding to two different time frames, were considered. The first type of models corresponds to quasi stationary conditions models, whilst the second type corresponds to faster processes.

Figure 2 shows the model of the air cooler. The difference (*DtTaw*) of inlet air temperature (*TiE*) and sea water temperature (*Tswi*) multiplied by the heat transfer coefficient determines the heat flow (*QE*). The heat flow is also related to the air flow (*GairE*) and the difference (*DtTE*) between inlet air temperature (*TiE*) and outlet air temperature (*ToE*). The air flow is also related to the difference (*DtPE*) between the inlet air pressure (*PiE*) and outlet air pressure (*PoE*) as indicated.

The qualitative model of the cylinders can be seen in Fig. 3 The air flow (*Gair*) multiplied by the fuel to air ratio (*Rm*) will determine the oil consumption (*Gcb*), which in turn if multiplied by the cylinder efficiency (*Ef*) will generate the output power (*Pot*). The exhaust gas flow (*Gg*) is related to the air flow and the difference (*DtTcb*) of the gases (*TgCyl*) and air inlet temperature (*TiCyl*) as shown.

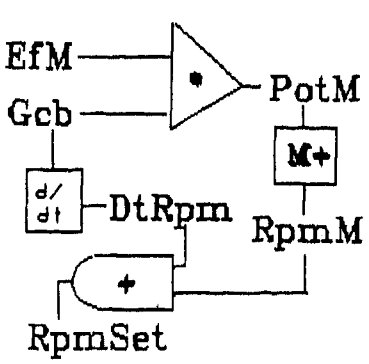

Fig. 4 Speed Regulator Model

Figure 4 shows a model of the engine speed regulator. The mechanical power given by the engine is the product of the oil compsumption (*Gcb*) by the efficiency (*EfM*). This power is related to the engine speed (*RpmM*) by a monotonic relationship. The speed governor has an integral type of control and the speed error (*DtRpm*) will increase the oil consumption as indicated. Notice that this model runs in a faster time frame that the models described before.

We consider a system to be a collection of interconnected components and the interaction between them to be a form of directional causality. Thus the behaviour of the system is obtained from the behaviour of each component and the connections between them (Williams,1990).
The Qualitative Simulation (Kuipers 1984;Kuipers 1986) begins with the propagation of the known information, or known disturbances, to the system through the constraints, in order to complete the description of the direction of change for each variable, at a given time-point.

SUPERVISOR STRUCTURE

The supervisor has being designed with two main objectives in mind: failure diagnosis and condition vigilance. The main characteristics of the supervisor are:

- Model based knowledge.
- Object-oriented implementation.
- Modular approach. Models are modules that can be interconnected into more complex models forming a natural hierarchical structure.
- Numeric information about the process is used.

In diagnosis process three tasks can be considered (Davis and Hamscher 1988): generating hypotheses by reasoning about symptoms, testing each hypothesis, and discriminating among those that survive testing. The supervisor perfoms the three tasks in a very similar way to the *hypothesize and match cycle* proposed in (Dvorak and Kuipers, 1988) as is indicated in the following.

Table 1: Normal Conditions

air receiver pressure, $PCol$	1589 bar
turbine speed. $RpmT$	7175 rpm
exhaust gas temperature inlet turbine, TiT	457.8 °C alarm
exhaust gas temperature outlet turbine, ToT	343.3°C
air temp.inlet compressor, TiC	37.7 °C
air temp. inlet cooler, TiE	144.3 °C
air temp. outlet cooler, ToE	35.9 °C
air receiver temp., $TCol$	43.6 °C
air flow, $Gair$	12.27 ton/h
air filter diff. pressure, $DtPF$	89 mmW
cooler diff. pressure, $DtPE$	98 mmW

Table 2: Abnormal Conditions

air receiver pressure, $PCol$	1769 bar
turbine speed. $RpmT$	6882 rpm
exhaust gas temperature inlet turbine, TiT	389.2 °C
exhaust gas temperature outlet turbine, ToT	282.8°C
comp. inlet air temp., TiC	35.4 °C
cooler inlet air temp., TiE	137.4 °C
cooler outlet air temp., ToE	38.1 °C
air receiver temp., $TCol$	45.0 °C
air flow, $Gair$	14.76 ton/h
air filter diff. pressure, $DtPF$	95 mmW
cooler diff. pressure, $DtPE$	143 mmW

Hipotheses generation. When any abnormal situation is encountered, the supervisor generates a set of hipotheses about the possible faults that led to that alarm. Hypotheses are generated by reasoning about symptoms with the help of influence graphs. These graphs describe how models and observations (alarms or incidences) are interconnected from a cause-reaction point of view. By transversing these graphs a list of possible defective modules or fault hypotheses can be made.

Hipotheses test. Each of the hipothesis is tested with the help of qualitative propagation of perturbations, qualitative simulation and heuristic rules. The models associated to each hypothesis are first initialized and then simulated.

The hypothesis test is done by comparing the simulation results to the observations. Those hypotheses producing results which do not match the observations are rejected.

Hipothesis discrimination. A diagnosis is produced by discriminating among those hipotheses that survived the test.

APPLICATION EXAMPLE

Two situations have been considered as illustrative examples, the first one corresponds to a diagnosis in a quasi state regime, whilst the second illustrates the Qualitative Simulation on a faster time scale case.

In the first case, the procedure starts when any deviations of the system ariables from their normal values is produced. The problem of diagnosis is to match these deviations with a hypothesis of fault or malfunction that justifies the observations.
Initially there is not a direct relationship (rule - made) between the observations and the hypothesis of fault. The reasoning about models must establish this association.

A full ahead quasi-static regime is considered. The normal values of the main variables for this state, which have been obtained with a numerical situation in the DPS 100 simulator of NORTHCONTROL, is given in table 1.

A malfunctioning of one of the elements is introduced in the simulator, originating an alarm in the exhaust gas temperature and other deviations from the normal situation values in other variables (table 2).

The transition between the normal and abnormal situations has been considered as a continuous transition in a specified time.
For the qualitative analisis we must express the state of these variables by means of its qualitative values and tendencies. The value of each variable is set by a landmark (written between brackets), which defines a qualitative value for the time points or by a pair of landmarks for the time intervals. The air flow $Gair$ is between a landmark value ($Gairt$) corresponding to to the full ahead normal engine regime and another landmark ($Gairst$) which represents the minimal air flow to ensure a complete combustion.
All air flow landmarks are placed in the following ordered space:

$$[\ 0....Gairst.....Gairt....+\infty\ ]$$

The tendency can take one of the three qualitative values *inc dec std.*
The abnormal situation can be expressed qualitatively as shown in table 3:

The hypothesis of a dirty air filter is made for trying to explain the abnormal state of the engine. This process is modelled by setting the tendency of the effective section of the filter SuF to be *dec*. By applying a heuristic rule, we get that the air flow through the filter $GairF$ decreases.

With this information the tendency of the air filter differential pressure could be *dec* as given by the observations.
Next by the connection between the filter model and the compressor model we can see what happens in the latter when the air flow decreases and the power suplies (an external variable) remain constant.

comp. speed	$RpmC$	$(0,RpmCt)$	*inc*
comp. outlet pressure	PoC	$(atm,PoCt)$	*inc*

In the cooler model we have an ambiguity (this is an essential feature of qualitative reasoning) with the tendency of the outlet air pressure PoE, because the inlet

Table 3: Qualitative Abnormal Conditions

Variable	Q. Value	Tend.
air rec. press.,*PCol*	*(atm,PoEt)*	*inc*
turbine speed,*RpmT*	*(0,RpmTt)*	*inc*
exhaust gas temp. inlet turbine,*TiT*	(*Tgt*,+∞)	*inc*
exhaust gas temp. outlet turbine,*ToT*	(*ToTt*,+∞)	*inc*
comp. inlet air temp.,*TiC*	*(Tsm)*	*std*
cooler in air temp.,*TiE*	*(ToCt)*	*std*
cooler out air temp.,*ToE*	*(ToEt)*	*std*
air receiver temp.,*TCol*	*(ToEt)*	*std*
air flow,*Gair*	*(Gairst,Gairt)*	*inc*
air filter diff. pressure,*DtPF*	*(DtPEt)*	*std*
cooler diff. press.,*DtPE*	*(0,DtPFt)*	*inc*

air pressure decreases *PiE,* but the difference pressure between input and output *DtPE* decreases too, so we cannot say anything about the tendency of *PoE*. To resolve this ambiguity we apply a KVL type heuristic rule proposed by De Kleer (De Kleer 1984):

if the input cooler pressure PiE changes, then the output cooler pressure will change in the same direction.

And we obtain

Cooler outlet press.	*PoE*	*(atm,PoEt)*	*dec*

from the cooler-receiver conection we get:

Air rec. pressure	*PCol*	*(atm,PoEt)*	*dec*

which matches the observations and corresponds to the malfunctioning that caused the abnormal deviations of the variables from the normal values. That is, by propagation of a disturbance (a hypothesis of malfunction) through all the models of the components we can infere the qualitative state of the variables. If they match the observations we can consider this hypothesis as a possible cause of the situation being analised.

For modelling complex systems we must make a hierarchical decomposition of them. This hierarchical decomposition includes time-scales (Kuipers, 1987). Models with similar time responses are grouped and the corresponding relationships between them are established. Thus a rapid model may have variables shared with a slower model.

To illustrate the second kind of model, running in a faster time frame, an example affecting the speed governor is given. The engine is considered to be in a stable state (all variables with *std* tendency) and a drop in the motor efficiency from its initial landmark (*EfM0*) to another landmark (*EfM1*), as shown in Fig. 5, is experimented.

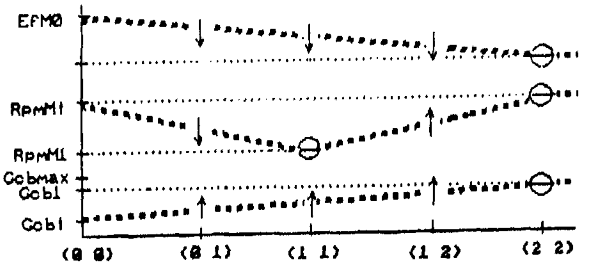

Fig. 5.a Qualitative Simulation, speed recovery

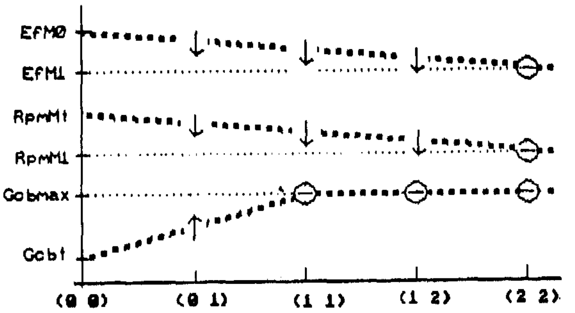

Fig. 5.b Qualitative Simulation, speed loss

If this tendency is propagated in the model all the rest of the variables will have a *dec* tendency except the oil consumption that will have an *inc* tendency. Various situations can be obtained from here, depending of which variables reach their landmarks first, as illustrated by Fig. 5.

The numeric response of the simulator for a determined efficiency is shown in Fig. 6. which corresponds to the qualitative simulation of Fig 5.a.

Figure 7 shows the diagram of the possible qualitative states that can be reached. The diagram tell us that there is a drop in the engine speed and that from there two basically different things may occur: the engine stabilizes its speed at the set point with an increase in oil consumption, or a lower speed regime is obtained with maximum oil consumption.

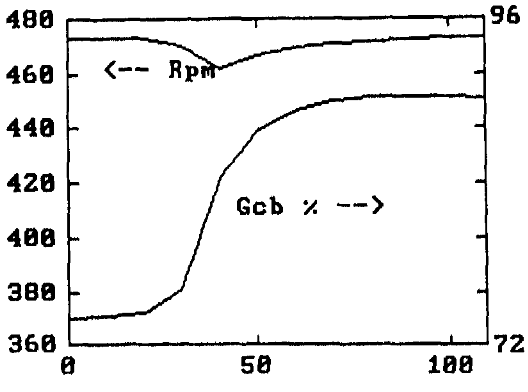

Fig. 6 Numerical Simulation

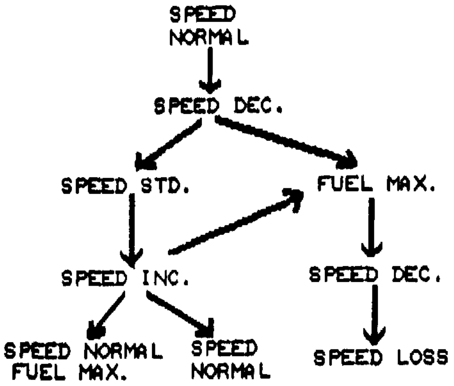

Fig. 7 Qualitative state diagram

Notice that the results of this rapid process (for example the value of the conbustible flow Gcb or the motor speed RpmM) can be incorporated into the slower processes for reasoning on a greater time scale.

CONCLUSIONS

It has been shown how qualitative models can be used for intelligent monitoring and supervision of the diesel engine turbocharger system of a ship. The qualitative models permit the kind of reasoning about physical systems, related to commonsense, that people can make. The object oriented approach has proved to be quite adequate for representing complex systems. A structure of classes for Qualitative Simulation has been proposed.

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