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FAULT MONITORING AND RE-CONFIGURABLE CONTROL FOR A SHIP PROPULSION PLANT

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SUMMARY

Minor faults in ship propulsion and their associated automation systems can cause dramatic reduction on ships' ability to propel and manoeuvre, and effective means are needed to prevent simple faults from developing into severe failure. The paper analyses the control system for a propulsion plant on a ferry. It is shown how fault detection, isolation and subsequent reconfiguration can cope with many faults that would otherwise have serious consequences. The paper emphasizes analysis of re-configuration possibilities as a necessary tool to obtain fault tolerance, showing how sensor fusion and control system reconfiguration can be systematically approached. Detector design is also treated and parameter adaptation within fault detectors is shown to be needed to locate non-additive propulsion machinery faults. Test trials with a ferry are used to validate the principles. © 1998 John Wiley & Sons, Ltd.

Key words: re-configuration; structural analysis; sensor fusion; ship propulsion; adaptive observer; fault detection

1. INTRODUCTION

Propulsion system availability is crucial for a ship's ability to manoeuvre. Nevertheless, control systems associated with propulsion have not been required to be either fail-operational or fault-tolerant. Instead, local safety systems protect machinery. They prevent continued operation or start-up if sensors inform that conditions are fulfilled to enter a local shut-down mode. While fail-safe for each piece of machinery, the local safety approach is not globally fail-safe for the ship. The result has been many events where consequences vary from irregularity to major economic loss and causalities. Several events could have been prevented if automation systems had been designed to be tolerant to faults with overall availability in mind.

Fault-tolerant control (FTC) is a methodology where analytical redundancy is employed using software that monitors the behaviour of components and function blocks. Without hardware redundancy, some faults may inevitably cause a plant shut-down, but the FTC strategy is that the majority of faults, and in particular the ones with severe consequences, are accommodated using intelligent work-around. The objective is to keep plant availability, but accept reduced performance as a trade-off. Recently suggested development methods within fault-tolerant control systems

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design offer a systematic approach to analysis of both fault propagation and of the services available from non-faulty components.

In this paper, an active solution to the FTC problem is employed where on-line fault detection and isolation can trigger a discrete event signal to a supervisor-agent when a fault is detected. The supervisor-agent will activate remedial actions based on either predetermined logic or on-line analysis and optimization.

This paper analyses the re-configuration possibilities available with a ship propulsion system consisting of a main engine with a controllable pitch propeller. Local control loops for shaft speed and propeller pitch, diesel engine overload control and co-ordinating functions for optimization and ship speed control are considered in the analysis.

The paper first discusses the roles of fault propagation analysis[1] and structural analysis[2] in design of fault-tolerant control systems. The components of the propulsion system are then described and services available from components are considered. A structural analysis is then carried out leading to a consistent scheme of re-configuration possibilities. The conditions are finally derived for a supervisor-agent which is supposed to carry out the actual re-configuration. Simulations on a model of a ferry[3] illustrate performance for a selected fault scenario.

2. COMPONENTS AND SERVICES

Autonomous fault-tolerant control requires fault detection and isolation followed by re-configuration in relevant units of the system. The units that are re-configurable are referred to as function blocks. These are parts of a system where control functions are implemented in software. When faults are detected and isolated, supervisory parts of the relevant controllers take action to implement a revised scheme, possibly with reduced performance when a fault has occurred. The re-configuration scheme can be determined at the design stage and stored as a static build-in function or it can be the result of real-time situation assessment and controller re-optimization. In both cases, analysis of fault propagation, mapping of system structure and listing of available services from components is necessary to determine which remedial actions are possible.

Prior work in this area include fault propagation analysis;[1] overall design ideas presented in References 4 and 5 made a comprehensive study and applied FTC on two real cases. The concept of structural analysis was introduced by Staroswiecki and Declerck[6] and refined in Reference 2. The use for residual generation for the ship benchmark[3] was presented in Reference 7, and analysis of components and services was treated by Staroswiecki and Gehin.[8] The present paper uses these ideas and make an extension to make this systematic approach applicable for re-configuration analysis and implementation of fault accommodation.

The analysis naturally starts with a block diagram of the plant considered, the ship propulsion system. Figure 1 shows components and signals for a ship propulsion plant. The diesel engine, shaft, propeller and hull are the main components. Two high power actuators control the machinery. One is an electro-mechanical positioner for fuel injection control of the diesel engine, and the other a hydraulic servo unit for pitch control of the propeller. Sensor signals include shaft speed, fuel index, propeller pitch and ship speed. Propulsion command is given by the set-point of a handle at the ship's bridge. More advanced control modes are optimal efficiency and ship speed control. An overload control block has authority over pitch and shaft speed commands. The control hierarchy is shown in Figure 2.

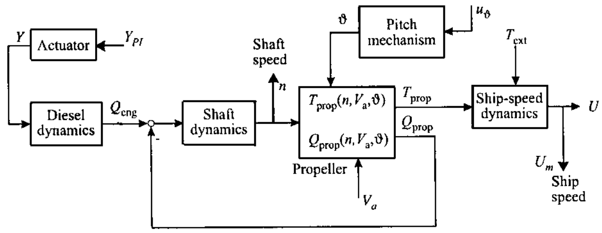

Figure 1. Structure of dynamic relations for the CP propeller, shaft and diesel engine

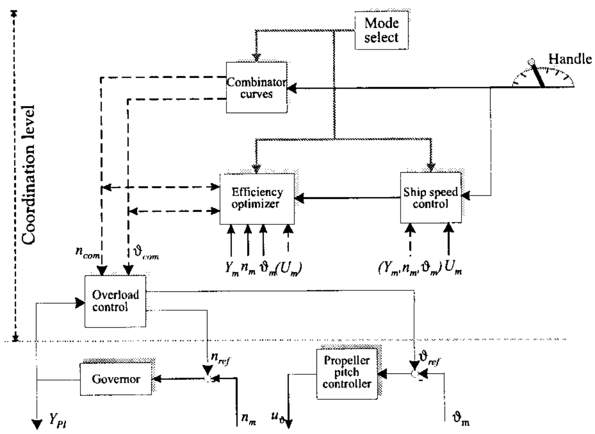

Figure 2. Hierarchy of controllers for the propulsion system. The handle gives input to a combinator, efficiency optimizer, and ship speed control. Lower level controls are shaft speed (governor), propeller pitch and diesel overload blocks

Table I. Physical component definitions for the shaft with diesel engine and controllable pitch propeller

Component	Normal service, {reduced(fault)
F_diesel: $Q_c = \mathrm{DE}\ (Y, K_Y)$	shaft torque, $\begin{cases} Q_c \text{ low (cyl.fault)} \\ \text{stop (luboil fault)} \end{cases}$
S_throttle: $Y_m = S_Y(Y)$	Measure index
S_shaftspeed: $n_m = S_n(n)$	Measure shaft speed
S_proppitch: $\theta_m = S_n(\theta)$	Measure prop. pitch
A_proppitch: $\theta = A_\theta(\dot{\theta}_c)$	Prop. pitch actuator, $\begin{cases} \text{drift (leakage)} \\ \text{stuck (mechanical fault)} \end{cases}$
S_shipspeed: $u_m = S_u(u)$	Meas. ship speed
S_handle: $h_d = \mathrm{HDL}(\cdot)$	Handle reference

Table II. List of symbols

Symbol	Unit	Explanation
f_{T_prop}	N	Thrust function
f_{Q_prop}	N m	Torque function
h_d	$-1..1$	Handle command
I_t	kg m^2	Total inertia
K_Y	N m	Torque coefficient
n	rad s^{-1}	Shaft speed
$R(u)$	N	Hull resistance
T_{prop}	N	Propeller thrust
T_{ext}	N	External force
$1-t$	-	Thrust deduction factor
u	m s^{-1}	Ship speed
V_a	m s^{-1}	Flow at propeller
$1-w$	-	Wake fraction
Q_{eng}	N m	Diesel torque
Q_f	N m	Shaft friction
Q_{prop}	N m	Propeller torque
Y	0..1	Fuel index
ϑ	$-1..1$	Propeller pitch

The different components can operate normally or they can suffer partial or full loss of functionality due to various physical failures. Fault propagation analysis[1] is used to define the possible effects of faults and their severity at the subsystem or system level. Fault propagation analysis tells how fault effects propagate throughout a system, and shows where fault accommodation is best applied. The structured analysis informs which services can be maintained with the help of the non-faulty parts of the system. Structural analysis thus provides the means to analyse how re-configuration can be accomplished. Fault propagation and structural analysis are hence complementary techniques to analyse a plant and subsequently design a fault tolerant control system for it.

Selected physical components of the ship propulsion plant are listed in Table I. The available service is listed for normal and fault conditions of each component. The static and dynamic characteristics of the individual components are discussed in the next section.

3. SHIP PROPULSION SYSTEM

This section introduces mathematical models for ship speed, propeller and prime mover, the essential propulsion system components. The purpose of the modelling is to obtain information to design fault detection and isolation (FDI) modules for essential faults and to give the prerequisites for design of re-configuration when faults occur. The block diagram in Figure 1 shows the structure of the propulsion system. See Table II for list of symbols.

3.1. Propeller thrust and torque

Controllable pitch (CP) propellers have blade angle (pitch) controlled by a hydraulic servo system. The developed thrust and torque are functions of pitch, shaft speed and flow velocity through the propeller

$$\begin{aligned} T_{\text{prop}} &= f_{T\_\text{prop}}(\vartheta, n, V_a) \\ Q_{\text{prop}} &= f_{Q\_\text{prop}}(\vartheta, n, V_a) \end{aligned} \tag{1}$$

These can be shown to approximately follow quadratic relations, for thrust

$$T_{\text{prop}} = T_{|n|n\vartheta}\vartheta|n|n + T_{nv}nV_a \tag{2}$$

and for torque

$$Q_{\text{prop}} = Q_0|n|n + Q_{nn|\vartheta|}|\vartheta||n|n + Q_{nv\vartheta}\vartheta|n|V_a \tag{3}$$

These relations give a quite good approximation in the steady-state cases whereas they are less applicable during large transients like crash stop. The term $Q_0|n|n$ accounts for the torque at zero pitch.

3.2. Diesel engine prime mover

Elaborate details of the dynamics[9] are not important in this context, but would be for detailed design of FDI for the engine. Here, diesel torque can be considered linearly related to the fuel index, without dynamics involved:

$$Q_{\text{eng}} = K_Y Y \tag{4}$$

The dynamics of propeller and shaft is merely that of rotating inertias subjected to torque balance between prime mover torque and load torques,

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}I_t n^2\right) = n(Q_{\text{eng}} - Q_{\text{prop}} - Q_{\text{f}}) \tag{5}$$

The dynamics of the prime mover and its control system is tightly coupled to the speed dynamics of the ship through the propeller (Equation (3)). The structure of prime mover control is also shown in Figure 2. The measured shaft speed is compared with a reference speed and the governor (speed controller) regulates the fuel injection to the engine to obtain the desired speed. Limit curves are incorporated for shaft-speed-dependent torque and air pressure.

3.3. Hull resistance

Ship's resistance to motion through the water can be described to the first order by a resistance curve, which is a third- to fifth-order polynomial in u. The order of the polynomial is higher the closer the ship operates into the wave making region. The resistance curve is known *a priori* but with some uncertainty. The first-order equation

$$m\dot{u} = R(u) + (1 - t)T_{\text{prop}} + T_{\text{ext}} \tag{6}$$

is a sufficient approximation in this context.

3.4. Actuators for fuel injection and propeller pitch

The actuators can both be modelled as first-order dynamic systems with limits in rate of change and in output. The electro-hydraulic pitch control system is described by the following equations:

$$u_{\dot{\vartheta}} = k_{\mathrm{t}}(\vartheta_{\mathrm{ref}} - \vartheta_m)$$
$$\dot{\vartheta} = \max(\dot{\vartheta}_{\min}, \min(u_{\dot{\vartheta}}, \dot{\vartheta}_{\max}))$$
$$\vartheta = \max(\vartheta_{\min}, \min(\vartheta, \vartheta_{\max}))$$

The diesel actuator is equivalent to this with command Y_{c} from the governor, rate limits $\dot{Y} \in [Y_{\mathrm{d}-}, Y_{\mathrm{d}+}]$ and output $Y \in [0, 1]$.

3.5. Sensors

Sensors for propeller pitch and fuel index are conventional angle transmitters.

Shaft speed is usually measured by a set of pulse pickups. A maximum logic selects the higher of the two signals. This protects against drop out of one of the pick ups but not against a 'high signal' fault or failure in a common processor/rate counter servicing both channels.

The ship speed is measured by magnetic log, Pitot tube or Doppler log. The former two measure water speed close to the hull and are quite prone to fluctuations from the turbulence and cross flow.

4. CONTROL HIERARCHY

The control hierarchy includes controllers for shaft speed, propeller pitch, diesel overload control, combinator curves from handle position to generate reference values of n and ϑ, efficiency optimization using n and ϑ and constant ship speed control. The signal flow between these function blocks is shown in Figure 1. The interested reader can find details about the control functions in Reference 3.

The input–output of each block is listed in Table III. The table lists the service of the function block in normal operation and the desired function in case of specific faults. The listing of desired remedial actions is a result of a combined fault propagation and structural analysis of the propulsion system, including the possibilities for re-configuration after serious faults. The function blocks are treated as virtual components. The difference in technological components is the ability to modify the functionality of function blocks triggered by events. The table lists their input and output, faults considered, and re-configuration possibilities. An example of this analysis is provided in the next section.

5. STRUCTURAL ANALYSIS

Structural analysis[2, 10, 6] is the study of properties which are independent of the actual values of the parameters. Only constraints (relations) between variables and parameters from the operating model are represented in this analysis. The constraints are independent of the system model and independent of the form under which this model is expressed (qualitative or quantitative data, analytical or non-analytical relations). The links are represented by a graph, or a table, on which the structural analysis is made.

Table III. Function blocks treated as virtual components

Function blocks	Service: normal, {reduced (fault)
$R_$combi: $\begin{bmatrix} n_{\rm d} \\ \vartheta_{\rm d} \end{bmatrix} = \mathrm{RCB}\ (h_{\rm d})$	(n, ϑ) demand, {freeze (input fault)
$C_$optim: $\begin{bmatrix} \mathrm{n_d} \\ \vartheta_{\rm d} \end{bmatrix} = C\_OP \begin{bmatrix} \mathrm{h_d} \\ \vartheta_m \\ n_m \\ Y_m \\ u_m \end{bmatrix}$	Best efficiency, $\begin{cases} \text{use estimate (inp. fault)} \\ \text{roll-back (ref. fault)} \\ \text{alter limits (diesel fault)} \end{cases}$
$C_$over: $\begin{bmatrix} n_{\rm r} \\ \vartheta_{\rm r} \end{bmatrix} = \mathrm{C\_OL} \begin{bmatrix} n_{\rm d} \\ \vartheta_{\rm d} \\ n_m \\ \vartheta_m \\ Y_m \end{bmatrix}$	Avoid overload, $\begin{cases} \text{freeze (fault)} \\ \text{use estimate (fault)} \end{cases}$
$C_$speed: $h_{\rm d} = \mathrm{C\_SS} \begin{bmatrix} u_{\rm r} \\ u_m \\ .. \end{bmatrix}$	constant u, $\begin{cases} \text{freeze } h_{\rm d} \ (u_m \text{ fault}) \\ \text{estimate } u_m \ (u_m \text{ fault}) \\ \text{roll-back } (u_{\rm r} \text{ fault}) \end{cases}$
$C_$shaft: $Y_{\rm c} = \mathrm{C\_SP}(n_{\rm r}, n_m)$	shaft control, $\begin{cases} \text{estimate } n \ (n_m \text{ fault}) \\ \text{roll-back } (n_{\rm r} \text{ fault}) \end{cases}$

5.1. *Description of the model*

The model of the system is considered as a set of constraints, $\mathscr{F} = \{f_1^{\rm c}, f_2^{\rm c}, \ldots, f_m^{\rm c}\}$ that are applied to a set of variables $\mathscr{Z} = X \cup \bar{X}$. X denotes the set of unknown variables while $\bar{X}$ is the set of known variables: sensor measurements, control variables (signals), variables with known values (constants, parameters) and reference variables (signals). The term constraint refers to the imposed relations between values of the variables. Variables are constrained by the physical laws applied to a particular unit. The constraints and variables for the propulsion system are listed in Table IV.

5.2. *Formal representation*

The structure of the system is described by the following binary relation:

$$S : \mathscr{F} \times \mathscr{Z} \to \{0, 1\}$$
$$(f_i^{\rm c}, z_j) \to \begin{matrix} S(f_i^{\rm c}, z_j) \\ S(f_i^{\rm c}, z_j) \end{matrix} = \begin{cases} 1 & \text{iff } f_i^{\rm c} \text{ applies to } z_j \\ 0 & \text{otherwise} \end{cases}$$

These relations can be represented by an incidence table or the equivalent digraph. Figure 3(a) shows the structural table for the propulsion system. Some constraints may be expressed through non-isomorphic mappings for certain variables. Such variables cannot be re-constructed through an inverse mapping from knowledge about remaining variables. Elements with this property are marked by M's (for multiple), replacing the 1's in the incidence table and unidirectional arcs in the corresponding digraph. An example of such a constraint is $f_8^{\rm c}$: it is always possible to compute the value of $Q_{\rm prop}$ from $f_8^{\rm c}$ when $\vartheta, n,$ and V_a are known. However, knowing the values

Table IV. Constraints and relations for the shaft

Constraint	Description
$f_1^c : n_m = n$	sensor_n
$f_2^c : \vartheta_m = \vartheta$	sensor_ϑ
$f_3^c : u_m = u$	sensor_u
$f_4^c : Y_m = Y$	sensor_Y
$f_5^c : K_Y = K_{Y\mathrm{c}}$	Engine gain
$f_6^c : Q_{\mathrm{eng}} = K_Y Y$	Engine torque
$f_7^c : -Q_{\mathrm{eng}} = Q_{\mathrm{prop}} + Q_{\mathrm{f}}$	Shaft torque balance
$f_8^c : Q_{\mathrm{prop}} = f_{Q_{\mathrm{prop}}}$	Propeller torque
$f_9^c : T_{\mathrm{prop}} = f_{T_{\mathrm{prop}}}$	Propeller thrust
$f_{10}^c : R(u) = f_{Ru}(u)$	Hull resistance
$f_{11}^c : R(u) = -T_{\mathrm{ext}} - (1-t)\,T_{\mathrm{prop}}$	Ship speed, force balance

of $Q_{\mathrm{prop}}, n,$ and V_a does not enable the calculation of a unique ϑ in all cases. This fact is not apparent from the equations in this paper but is apparent when looking at the underlying propeller characteristics. The non-isomorphic problem for the Q_{prop} relation is only present in a narrow range of transient conditions (during crash stop).

5.3. Sensor fusion for re-configuration

In control systems, re-configuration can be obtained either by means of hardware redundancy or the use of software redundancy. In the case where hardware redundancy exists, the scope of design is FDI algorithms and hardware switching. When analytic redundancy is available, fault tolerance is obtained by means of sensor fusion: the value of the signal which is lost or corrupted due to faults, is reconstructed using known values of other signals. If controllers fail, alternative control goals must be defined and executed with remaining operational equipment.

The structural analysis approach is usually employed to obtain analytical redundancy relations for FDI.[7] It can, however, be used without difficulties for sensor fusion as well, since a constraint relation can be used to re-construct a signal from the other measured variables. An example for the propulsion system is a critical fault in the shaft speed measurement which can be accommodated by estimating shaft speed from other available measurements.

5.3.1. Fault in the shaft speed measurement A critical fault in the propulsion system is a fault in the measurement of shaft speed. The constraint f_1^c represents this device in Table IV. A fault occurrence means that the constraint f_1^c does not hold, e.g. the values of the variable n_m are not correctly related to the values of the variable n. Figure 3(b) shows that variable n is involved in three relations which are specified by the constraints f_1^c, f_8^c, and f_9^c. Since the constraint f_1^c is not valid, there are two other possible ways of calculating the values of the variable n, namely through constraints f_8^c and f_9^c. As shown in Figure 4(a) and 4(b), the ship speed can be described

	n_m	ϑ_m	u_m	Y_m	K_{yc}	n	ϑ	u	Y	K_y	Q_{eng}	Q_{prop}	T_{prop}	$R(u)$
f_1^c	1					1								
f_2^c		1					1							
f_3^c			1					1						
f_4^c				1					1					
f_5^c					1					1				
f_6^c									1	1	1			
f_7^c											1	1		
f_8^c						1	M	1				1		
f_9^c						1	M	1					1	
f_{10}^c								1						1
f_{11}^c													1	1

a)

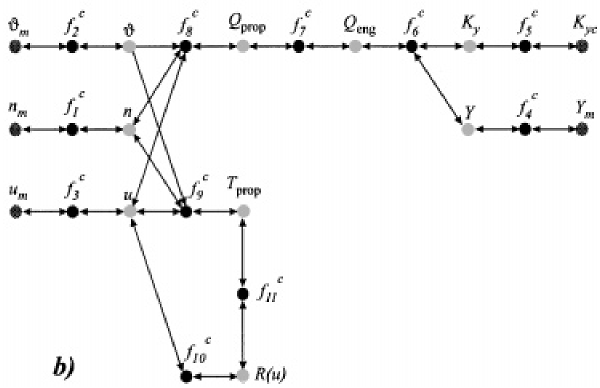

Figure 3. (a) The structural representation of the model by a (binary) table. 1's are replaced by ×'s to indicate causality (calculability) between variables. (b) Corresponding digraph representation

as a function of the other known variable as

$$\hat{n}_q = f_q(\vartheta_m, Y_m, K_{yc}, u_m) \tag{7}$$

$$\hat{n}_t = f_t(\vartheta_m, u_m) \tag{8}$$

The process to apply the sensor fusion based on this approach is the following:

For the particular variable (for instance n) identify the set of related constraints (f_8^c and f_9^c) and

1. choose one of the available constraints,
2. remove all other constraints in the set and their associated arcs,
3. for all the variables connected to the chosen constraint search backward until a known variable for each is reached.

By examining all the constraints, the set of equations/relations by which the variable can be calculated is identified and can be used for re-configuration purposes. For the shaft speed failure,

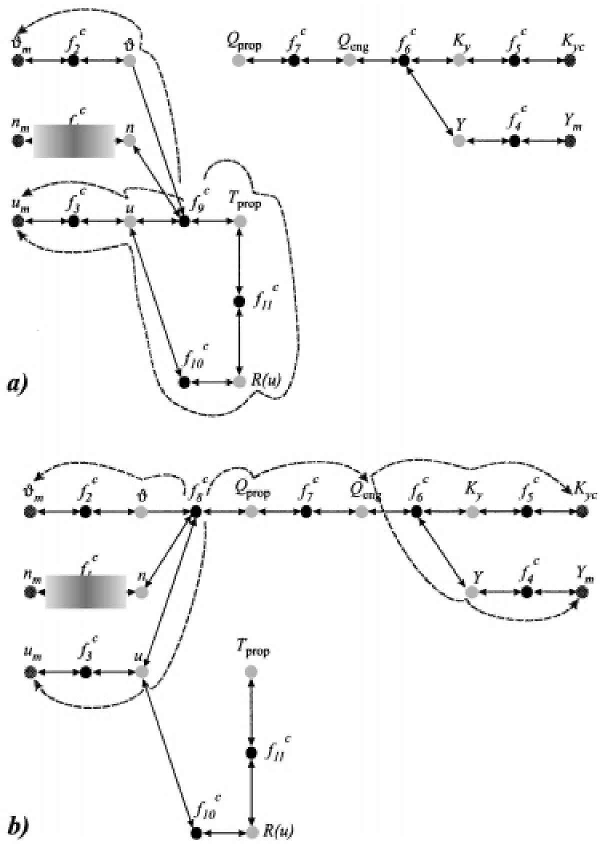

Figure 4. Sensor fusion methods based on structural representation: shaft speed calculation through (a) propeller thrust equations f_9^c and (b) propeller torque equation f_8^c

the method is illustrated graphically in Figures 4(a) and 4(b). Grey dashed arrows show the calculation paths to the known variables.

Using quadratic representation of the propeller torque, the variable n can be estimated from the constraint f_8^c:

$$\hat{n}_q = -\frac{Q_{nv\vartheta}(1-w)u_m\vartheta_m}{2Q_{nn\vartheta}\vartheta_m}\left(1+\sqrt{1+\frac{4Q_{nn\vartheta}\vartheta_m K_{Y\mathrm{c}} Y_m}{(Q_{nv\vartheta}(1-w)u_m\vartheta_m)^2}}\right) \tag{9}$$

The estimation of n based on static relations is obviously too primitive to give a good estimate. A non-linear observer should give better estimation during transients.

6. DETECTION OF SHAFT SPEED AND ENGINE FAULTS

This section deals with the problem of detecting whether a shaft speed fault is present. The relevant dynamics to be considered was described above, leading to the constraints f_6 to f_{11}. The task at hand is to estimate a signal fault in n_m and a parameter fault K_Y. The dynamic equations directly determining shaft speed are

$$
\begin{aligned}
I_t \dot{n} &= Q_{\text{eng}} - Q_{\text{prop}} - Q_f \\
Q_{\text{eng}} &= K_Y Y_m
\end{aligned}
\tag{10}
$$

Taking the ship speed U as a measured variable, which is a valid assumption when U_m is non-faulty,

$$Q_{\text{prop}} = Q_0|n|n + Q_{\vartheta nn}|\vartheta||n|n + Q_{\vartheta nv}\vartheta|n|(1-w_0)U_m \tag{11}$$

In the sequel, we use $Q_{\vartheta nU} \equiv Q_{\vartheta nv}(1-w_0)$ for brevity.

The shaft speed is positive in a controllable pitch installation, so

$$\dot{n} = \frac{1}{I_t}(K_Y Y_m - Q_f - Q_0 n^2 - Q_{\vartheta nn}|\vartheta|n^2 - Q_{\vartheta nU}\vartheta n U_m) \tag{12}$$

Following the benchmark definition of Izadi-Zamanabadi and Blanke[11], we need to consider faults in either shaft speed measurement or in the diesel torque coefficient,

$$n_m = n + n_f \tag{13}$$

and

$$K_Y = K_{Yc} - K_{Yf} \tag{14}$$

The detection task is hence increased from a single fault shaft speed sensor fault detection to a more complex one of simultaneous additive and non-additive faults.

6.1. Adaptive observer

The dynamic relation (12) can be written in a form which is linear in the unknown parameter

$$
\begin{aligned}
\dot{x} &= \Phi(x, u_2, u_3) + \theta u_1 \\
y &= x
\end{aligned}
\tag{15}
$$

using

$$
\begin{aligned}
&\Phi = \frac{1}{I_t}(-Q_{\vartheta nn}|\vartheta|n^2 - Q_{\vartheta nU}\vartheta n U_m - Q_0 n^2 - Q_f) \\
&x = n,\ u_1 = Y_m,\ u_2 = U_m,\ u_3 = \vartheta_m,\ \theta = \frac{K_Y}{I_t}
\end{aligned}
\tag{16}
$$

An adaptive observer can then be built by using measured inputs: Y_m, U_m, ϑ_m and measured state n_m.

It is noted that the more general case was treated in Reference 12. However, the detailed assessment of the Lipshitz conditions that determine the gains in the adaptive observer are easily made too conservative to get useful results. A few comments are thus considered appropriate. This leads to the following theorem.

Theorem 1

An adaptive observer for the problem

$$\dot{n} = \frac{1}{I_t}(K_Y Y_m - Q_{\vartheta nn}|\vartheta|n^2 - Q_{\vartheta nU}\vartheta n U_m - Q_0 n^2 - Q_f) \tag{17}$$

is the state estimator

$$\dot{\hat{n}} = \frac{1}{I_{\mathrm{t}}}(-Q_{\vartheta nn}\vartheta_m\hat{n}^2 - Q_{\vartheta nU}\vartheta_m\hat{n}U_m - Q_0\hat{n}^2 - Q_{\mathrm{f}}) + Y_m\hat{\theta} + L(n_m - \hat{n}) \tag{18}$$

with parameter updating

$$\dot{\hat{\theta}} = PY_m(n_m - \hat{n}) \tag{19}$$

The adaptive observer is globally asymptotically stable with the scalar gains

$$P > 0, \qquad L > \frac{Q_{\mathrm{eng,\ max}}}{I_{\mathrm{t}}\, n_{\max}}\left(\alpha\frac{n_{\max}}{n_{\min}} + \beta\right) \tag{20}$$

where I_{t}, $Q_{\mathrm{eng,max}}$, $n_{\max}, n_{\min}$, α *and* β *are plant-specific parameters.*

Proof. The non-linear torque function

$$\Phi(n,u) = \frac{1}{I_{\mathrm{t}}}(-Q_{\vartheta nn}|\vartheta_m|n^2 - Q_{\vartheta nU}\,\vartheta_m n U_m - Q_0 n^2 - Q_{\mathrm{f}}) \tag{21}$$

is Lipshitz

$$\|\Phi(n,u) - \Phi(\hat{n},u)\| < \gamma\|n - \hat{n}\| \tag{22}$$

since

$$\begin{aligned}
&\Phi(n,u) - \Phi(\hat{n},u)\\
&\quad = \frac{1}{I_{\mathrm{t}}}(n - \hat{n})((-Q_0 - Q_{\vartheta nn}|\vartheta_m|)(n + \hat{n}) - Q_{\vartheta nU}\vartheta_m U_m)\\
&\quad = \frac{1}{I_{\mathrm{t}}}(-((Q_0 + Q_{\vartheta nn}|\vartheta_m|)n + Q_{\vartheta nU}\vartheta_m U_m) - (Q_0 + Q_{\vartheta nn}|\vartheta_m|)\hat{n})(n - \hat{n})
\end{aligned} \tag{23}$$

Practical diesel torque constraints and ship speed being dynamically related to torque lead to

$$-((Q_0 + Q_{\vartheta nn}|\vartheta_m|)n + Q_{\vartheta nU}\vartheta_m U_m) < \alpha\frac{Q_{\mathrm{eng,\ max}}}{n_{\min}} - (Q_0 + Q_{\vartheta nn}|\vartheta_m|)\hat{n} < \beta\frac{Q_{\mathrm{eng,max}}}{n_{\max}} \tag{24}$$

Hence

$$\|\Phi(n,u) - \Phi(\hat{n},u)\| < \gamma\|n - \hat{n}\| \tag{25}$$

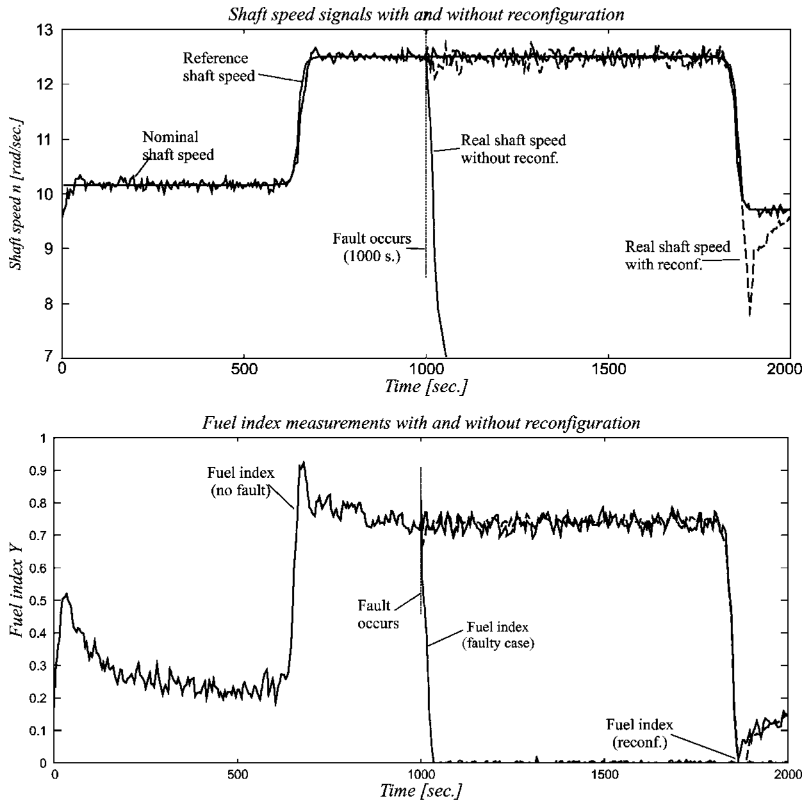

Figure 5. Shaft speed and fuel index for nominal, faulty and re-configured cases using static relation

where the Lipshitz coefficient is

$$\gamma = \frac{Q_{\mathrm{eng,max}}}{I_{\mathrm{t}}\, n_{\max}} \left(\alpha \frac{n_{\max}}{n_{\min}} + \beta \right) \tag{26}$$

A Lyapunov function for the observer error

$$\tilde{n} = n - \hat{n}, \qquad \tilde{\theta} = \theta - \hat{\theta} \tag{27}$$

is $V = nPn^{\mathrm{T}} + \theta\theta^{\mathrm{T}}$, where $P > 0$ is a scalar. Then, using notation 16, and details of the proof in Reference 12,

$$\dot{V} = 2(\Phi(n,u) - \Phi(\hat{n},u))P\tilde{n} + 2u_1\tilde{\theta}P\tilde{n} - 2\tilde{n}LP\tilde{n} + 2\tilde{\theta}\frac{\mathrm{d}\tilde{\theta}}{\mathrm{d}t} < 0 \tag{28}$$

iff

$$L > \gamma, \quad P > 0$$

and $n \subseteq [0, n_{\max}]$, $\hat{n} \subseteq [0, n_{\max}]$.

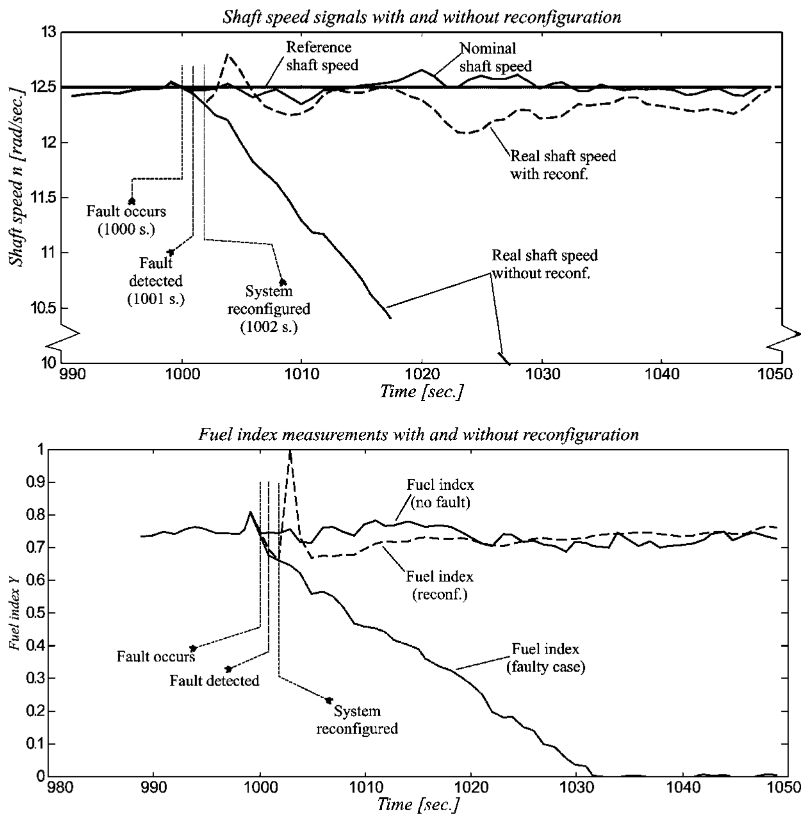

Figure 6. A zoom in on the shaft speed and fuel index for nominal, faulty and re-configured cases using static relations

Remark 1

The parameters to calculate the γ value are, typically $\alpha = 0{\cdot}1$, $\beta = 3$, $n_{\max} = 3n_{\min}$. The α and β values are found from Equations 6 and 12 using the observation that maximum shaft speed is limited to $1.09n_{\text{nom}}$ even during crash stop of a ship.

Remark 2

The propeller coefficients are taken to be known parameters in the observer. With inherent parameter uncertainty, parameter adaption, Equation (19) is needed. Parameter convergence will require persistent excitation.

6.2. Re-configuration

Re-configuration to accommodate the n fault is then to switch the controller to use the estimate of n instead of the faulty measurement n_m. When a gain fault of the engine has occurred, the remedial is to change the overload limits within the governor to the reduced capability available

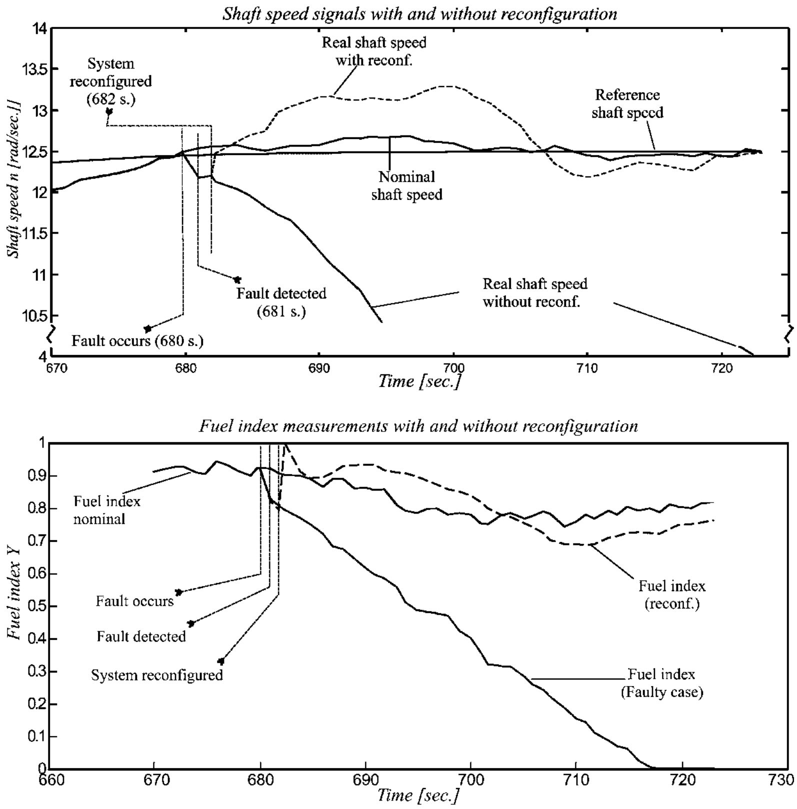

Figure 7. A zoom in on the shaft speed and fuel index values in the worst case using static relation

from the engine. Since the two reactions are entirely different, proper isolation of the two faults is crucial.

Detection and isolation of a change is done using standard methods for change detection. This is not immediately possible with only one residual; redundant information in the system is needed. The possibilities can be derived from the structure diagrams. They show that observation of ship speed through the thrust constraints can be used.

The slow dynamics of ship speed, and the fast reactions of a diesel engine make it necessary, however, to assume a worst-case fault in the shaft speed measurement. When a discrepancy in $\tilde{n}$ is observed, diesel control is maintained using the open-loop non-linear observer. In due time, other measures will show whether the fault was the less serious cylinder defect of the engine, and the re-configurated sensor signal could be switched to normal, while other appropriate steps are taken to accommodate the fault now isolated.

The simulations show the performance of the adaptive observer with re-configuration when a shaft speed sensor failure occurs.

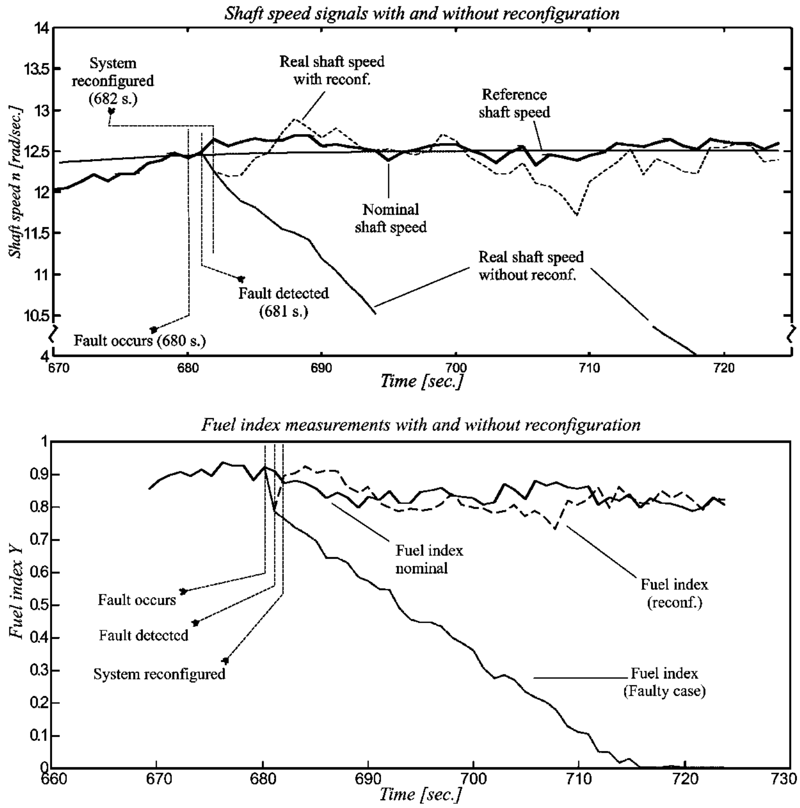

Figure 8. A zoom in on the shaft speed and fuel index values in the worst case, using the nonlinear observer generated shaft speed

7. SIMULATION RESULTS

The two methods are applied to the ship propulsion benchmark where the following scenario is simulated. A shaft sensor failure occurs at time 1000 s. A statistical fault detection method (CUSUM) has detected the sensor failing high at time 1001 s. The supervisor accommodates the fault at time 1002 s by activating a dedicated procedure that estimates the variable n through equation (9). The calculated variable replaces the measured one in the shaft speed control loop.

The upper part of Figure 5 shows the real shaft speed for nominal, faulty and re-configured cases. The lower part shows the fuel index. The failure occurs during ocean passage without transients in handle demand. A zoom in is shown in Figure 6. The figure shows that switching from the faulty n_m to the calculated $\hat{n}_q$ results in an overshoot of 2% in shaft speed. Figure 7 shows a zoom in at the time responses when the fault occurs exactly at the worst time, during a transient caused by alteration of the handle command simultaneously with the diesel torque being close to the maximum limit. The transient following the fault causes the overload controller to rapidly reduce the pitch angle. This rapid load reduction makes it difficult for the shaft speed controller to reduce the shaft speed. In this extreme case, the overshoot in shaft speed is 8%, very close to the critical limit of over-speed shut down of the main engine, which is 9% in this installation. Wave-induced shaft speed fluctuation would easily make the shaft speed reach the shut-down limit. The use of the non-linear observer for fault detection, and subsequently for estimation of shaft speed is shown in Figure 8. The resulting overshoot in this case is not more than 2%, which is rather satisfactory and well below the over-speed limit. In each of the figures, the curves represent the following cases: normal case (solid line), faulty case (dash dotted line), and re-configured case (dashed line), reference signal (dotted line).

8. CONCLUSIONS

This paper analysed the re-configuration possibilities for a ship propulsion system with a main engine and a controllable pitch propeller and it was demonstrated how fault tolerance could be achieved against a critical sensor failure. The components of the propulsion system were described and available services considered in normal conditions and when failure occurred. A structural analysis was used to obtain a scheme of consistent re-configuration possibilities when the goal was to achieve uninterrupted prime propulsion of the ship. A non-linear, adaptive observer was adopted for fault detection and re-configuration. Simulations on a model of a ferry illustrated how a critical failure of the shaft speed measurement could be accommodated by the controller, within a framework of software based re-configuration. The penalty in control quality was found to be quite small and certainly acceptable against the alternative, which was a temporal loss of main propulsion of the ship.

The essential contributions of the paper were combining structural analysis and re-configuration design using a non-linear adaptive observer, and applying this approach to a realistic case.

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