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Residual Generation for the Ship Benchmark Using Structural Approach

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Abstract: The prime objective of Fault-tolerant Control (FTC) systems is to handle faults and discrepancies using appropriate accommodation policies. The issue of obtaining information about various parameters and signals, which have to be monitored for fault detection purposes, becomes a rigorous task with the growing number of subsystems. The structural approach, presented in this paper, constitutes a general framework for providing information when the system becomes complex. The methodology of this approach is illustrated on the ship propulsion benchmark.

Keywords: Structural analysis, analytical redundancy relations, fault detection and Isolation

1 INTRODUCTION

In complex systems, continued operation of various subsystems has both economic and safety implications [1] . The primary objective of Fault-Tolerant Control (FTC) systems is to handle faults and discrepancies by accommodating for them whenever they occur. Detection and Isolation of abnormal situations are thus the first stages for FTC. Three sources of faults can be, in general, considered: 1) sensing devices (various hardware and software sensors), 2) actuating devices (controllers + actuators, PLC's , etc.), 3) the evolving parts of the system, which are the physical parts of the plant.
The accommodation strategy for the evolving and actuating parts is simple and straightforward: they will be substituted with the similar ones that are used as backups. On the other hand, it is quite obvious that the main part of the reconfiguration possibilities is placed on the controller/sensor part of the system. Controllers use set of signals (known, measured, and/or estimated), to calculate and deduce new actions which then are carried out by the corresponding actuators.
Consequently, to achieve FTC it is necessary to validate the information which will be used by corresponding control strategies/algorithms. This is the task of Fault Detection and Isolation (FDI) algorithms. Using model based FDI methods ([2], [3]), the first step generates a set of residuals which express the difference between the information provided by the system and the one given by its model in normal operation.
This paper presents the structural approach ([4], [5], [6]) that can provide information about which signals/parameters can or can not be monitored or validated. Furthermore, by using this approach, one can determine the calculation sequences of the residuals. It is also possible to obtain structured residuals which fulfill required robustness properties [7]. This approach, using well-known

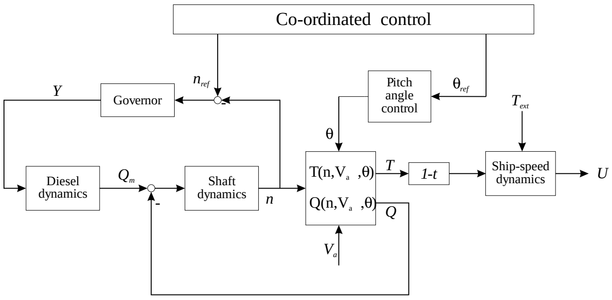


Fig. 1. Diagram of the ship speed propulsion system

digraph theory, constitutes a general framework which shows its advantage when the number of components/subsystems in a complex system increases. The structural approach is been applied on the ship propulsion benchmark presented in Safeprocess97 [8]. The model, used in this paper, constitutes of two parts, the dynamic part and the static one. The major part of the former is a linear version of the benchmark while the later is represented by tables. As the result, the obtained overall model has maintained the complexity of the plant. Using the structural analysis the residual calculation form are determined and some simulation results in faulty situations end this paper.

2 SHIP BENCHMARK

2.1 Description of the model

An outline of the propulsion system is drawn in Fig. 1. The model of the system is considered as a set of constraints, $\mathcal{F} = \{f_1, f_2, , \cdots, f_m\}$, which are applied to a set of variables $\mathcal{Z} = X \cup \bar{X}$. X denotes the set of unknown variables while $\bar{X}$ denotes 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 fact that a technological unit imposes some relations between the values of the variables, so that taking any possible value in the variable space except those compatible with the physical laws applied to that technological unit, is not possible. The defined constraints and variables for the ship propulsion benchmark are given in the following by referring to the benchmark [8], and figure 1.

2.1.1 Propeller pitch angle control loop The linearized version of the pitch angle control system is described by the following equations:

$$
\begin{aligned}
f_1 &: \; u_c = k_t\,(\theta_{ref} - \theta_m) + (\Delta\dot{\theta}_{inc}) \\
f_2 &: \; u_c = \dot{\theta} \\
f_3 &: \; \theta_m = \theta + \nu_\theta + (\Delta\theta_m)
\end{aligned}
$$

k_t is the proportional controller's gain, θ_{ref} is the reference signal, θ_m is the measured signal, and u_c is the control signal. $\Delta\dot{\theta}_{inc}$ and $\Delta\theta_m$ are incipient correspondingly sensor fault occurred in this system. There are hence three constraints defined for this model, f_1, f_2, and f_3.

2.1.2 Governor Input to the Governor (PI controller), is the difference between the shaft speed reference n_{ref}, and the measured shaft speed n_m. The output is the fuel index Y_c. The PI controller is described by the following constraints:

$$
\begin{aligned}
f_4 &: \; \dot{Y}_{PI} = \frac{k_r}{\tau_i}[(n_{ref} - n_m) + \tau_i \frac{d\,(n_{ref} - n_m)}{dt}] \\
f_5 &: \; Y_{PI} = \int \dot{Y}_{PI}.dt + Y_{PI_0} \\
f_6 &: \; Y_c = \max(0, \min(Y_{PI}, 1)) \\
f_7 &: \; Y_m = Y_c + \nu_Y
\end{aligned}
$$

The dependence of the governor to the shaft speed is disregarded. Y_{PI_0} is the initial value for fuel index. Y_m is the measured fuel index.

2.1.3 Diesel engine dynamics The diesel engine dynamics can be divided in two parts. The first part, which describes the relation between the generated torque and the fuel index, is given by the following constraint:

$$
\begin{aligned}
&f_8 : k_y = k_{yc} + \Delta k_y \\
&f_9 : Q_m + \tau_c \frac{dQ_m}{dt} = k_y.Y_c \Longleftrightarrow Q_m = ce^{-\frac{t}{\tau_c}} + k_y.Y_c
\end{aligned}
$$

k_{yc} is the diesel engine gain constant, τ_c the engine's time constant. The value of parameter c is calculated by inserting initial values of the ODE. The second part of the engine dynamics is given by the following constraint:

$$f_{10} : I_m \dot{n} = Q_m - Q$$

Q_m is the torque developed by the diesel engine, Q is the developed torque from propeller dynamics. The shaft speed is then calculated by:

$$f_{11} : n = \int \dot{n}.dt + n_0$$

2.1.4 Propeller characteristics The propeller characteristics are represented in the benchmark by two tables of real data: the first table characterizes the developed (consumed) propeller torque Q, and the second table characterizes the developed (produced) propeller thrust T:

$$
\begin{aligned}
&f_{12} : f_Q(n, \theta, U(1-w), Q) = 0 : Table1 \\
&f_{13} : f_T(n, \theta, U(1-w), T) = 0 : Table2
\end{aligned}
$$

where U is the ship speed. w is a hull and propeller dependent parameter and is called wake fraction.

2.1.5 Ship speed dynamics The following constraints describe the ship speed dynamics:

$$\begin{aligned} f_{14} &: \; m.\dot{U} = R_U + (1 - t_T)T \\ f_{15} &: \; U = \int \dot{U}.dt + U_0 \\ f_{16} &: \; U_m = U + \nu_U \\ f_{17} &: \; R_U = R(U) : Table3 \end{aligned}$$

The hull resistance given by a table of real data, $R(U)$, describes the resistance of the ship in the water and is a negative quantity. Thrust deduction number t_T represents lost in thrust produced by propellers, due to propeller movements in the water. ν_U is the measurement noise. The remaining constraint is the sensor measurement for the shaft speed:

$$f_{18} : n_m = n + \nu_n (+\Delta n_m)$$

2.2 Fault characteristics

All benchmark faults are considered in this paper. The time intervals for different fault events are shown in the following table together with a short description of their nature.

Event	**Start time**	**End time**	**Type of fault**
$\Delta\theta_{high}$	180 s	210 s	pitch sensor high
$\Delta\theta_{low}$	1890 s	1920 s	pitch sensor low
$\Delta\dot{\theta}_{inc}$	800 s	1700 s	Inc. fault in control sig.
Δn_{high}	680 s	710 s	shaft speed sensor high
Δn_{low}	2640 s	2670 s	shaft speed sensor low
Δk_y	3000 s	3500 s	diesel engine gain drop

The fault Δk_y corresponds to 20% drop in the diesel engine motor gain k_{yc}. The total simulation time is 3500 sec..

3 STRUCTURAL ANALYSIS

The main principle of model based FDI (Failure Detection an Isolation) methods [2], [3] is to compare the behavior of the actual plant with the one given by a mathematical model. The first step of these approaches is to generate a set of residuals. These are the result of the on-line calculation of particular relations (called Analytical Redundancy Relations : ARR) which link only the known variables of the system. So, the residuals characterize the system operating mode: close to zero in normal operation and different from zero in faulty situation.

The advantage of the structural approach is twofold: it determines the part(s) of the system on which some ARR can be generated, and it is used to obtain the calculation sequences of the ARR.

The structural analysis is the study of the properties which are independent of the actual values of the parameters. Only links between the variables and parameters which result from the operating model are represented in this analysis. They are independent from the operating model and are thus independent of the form under which this operating model is expressed (qualitative or quantitative data, analytical or non-analytical relations). The links are represented by a graph, on which a structural analysis is performed.

	Y_m	n_m	U_m	θ_m	n_{ref}	θ_{ref}	k_{yc}	u_c	$\dot{Y}_{PI}$	Y_{PI}	Y_c	Q_m	$\dot{n}$	n	θ	k_y	$\dot{U}$	U	Q	T	R_U
f_1				1		1		1													
f_2								1							x						
f_3				1											1						
f_4		1			1				1												
f_5									1	x											
f_6										x	1										
f_7	1										1										
f_8							1									1					
f_9											1	x				1					
f_{10}												1	1						1		
f_{11}													1	x							
f_{12}														x	x			x	1		
f_{13}														x	x			x		1	
f_{14}																	1			1	1
f_{15}																	1	x			
f_{16}			1															1			
f_{17}																		x			1
f_{18}		1												1							

Fig. 2. The structural representation as a (binary) table. 1's are replaced by ×'s to indicate causality between variables.

The set of constraints for the ship model is $\mathcal{F} = \{f_1, f_2, \cdots, f_{18}\}$. The set of unknown variables is $X = \{\theta, n, u_c, \dot{Y}_{PI}, Y_{PI}, Y_c, Q_m, \dot{n}, k_y, \dot{U}, U, Q, T, R_U\}$ and the set of the known variables is $\bar{X} = \{Y_m, n_m, U_m, \theta_m, n_{ref}, \theta_{ref}, k_{yc}\}$.
The structure is described by the following binary relation:

$$\begin{aligned} S : \mathcal{F} \times \mathcal{Z} &\rightarrow \{0, 1\} \\ (f_i, z_j) &\rightarrow \begin{cases} S(f_i, z_j) = 1 \text{ iff } f_i \text{ applies to } z_j, \\ S(f_i, z_j) = 0 \text{ otherwise.} \end{cases} \end{aligned}$$

The structure of the considered system can be represented by a table or equivalently by a digraph as there exists a surjective mapping between these two representations. Figure 2 shows the structural table for the benchmark while the causality between variables are taken into considerations. The causality constraints are highlighted by replacing 1's by ×'s. An example for causal constraint is the constraint f_6: it is always possible to compute the value of Y_c from the constraint f_6 whenever the value of Y_{PI} is known, but the opposite is not possible.

The elimination procedure of the unknown variables in the equations of the system results in obtaining the ARR. An analysis of the structural model can give a guideline to carry out this elimination. The procedure is based on the notion of complete matching in a digraph [9]. A possible

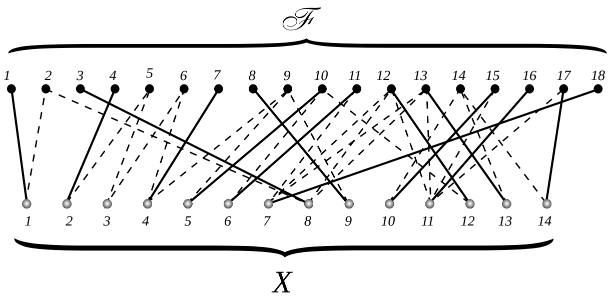


Fig. 3. A possible matching

matching for the benchmark is shown in figure 3. It should be mentioned that the possible matching in figure 3 is in fact a causal matching as well.

From a general point of view, the matching procedure allows to decompose the structural model into a canonical form, from which 3 types of subsystems are ensued:

- *just-determined* subsystem : all the unknown variables can be expressed as functions of the known variables
- *under-determined* subsystem : some unknown variables can't be expressed as functions of the known variables
- *over-determined* subsystem : some unknown variables can be expressed by different ways, as function of the known variables.

The over-determined subsystem defines the monitorable part of the system. The structural model of the ship, shown in figure 2, is decomposed into an under-determined subsystem and an over-determined subsystem. The existence of the under-determined subsystem is due to constraints f_5 and f_6 where the unknown variable Y_{PI} can not be explicitly determined as function of variables Y_c and $\dot{Y}_{PI}$.

In the over-determined subsystem, three constraints : f_2, f_9, and f_{14} are not used to perform the matching and thus can be used to generate three ARRs. The way to obtain these can be represented graphically as shown in figure 4. These graphs are oriented ones since they take into account calculability constraints which express that the functions can or can not be inverted.

Remark: There exists several possibilities of complete matching on the ship structural model. But one can show that the obtained graphs (a, b, and c) are the same whatever the chosen matching.

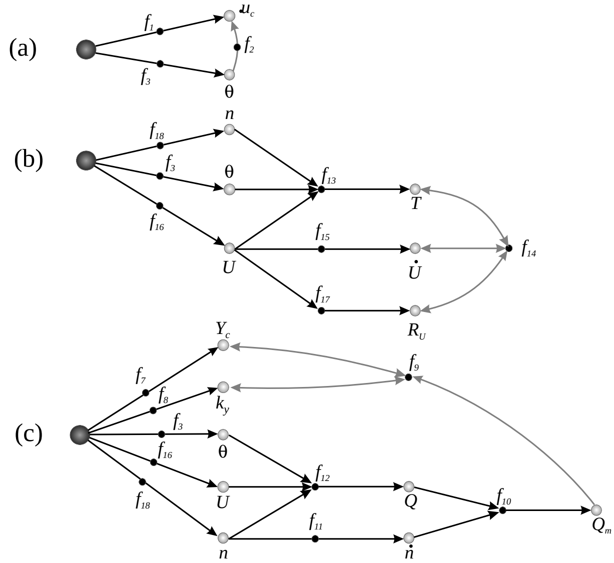


Fig. 4. Decomposition of the over-determined part of the system represented by its digraph. The big dark circles represent the available data at any time.

3.1 *Residual expressions*

The ARR calculation sequences are directly deduced from these graphs. For instance, let's consider the case a). The two unknown variables u_c and θ can respectively be calculated using f_1 and f_3. The ARR expression is obtained using the function f_2:

$$\frac{d\theta_m}{dt} - k_t.(\theta_{ref} - \theta_m) = 0$$

A residual is the result of the calculation of an ARR when the known variables are replaced by their values. Two residual expressions can thus be deduced: the *calculation* form, which allows to calculate the residual value and the *evaluation* form, which allows to explain this obtained residual value. The calculation expressions for residuals r_1, r_2, and r_3, deduced from corresponding subgraphs (a), (b), and (c) in figure 4 are:

$$\begin{aligned}
r_1 &= \frac{d\theta_m}{dt} - k_t.(\theta_{ref} - \theta_m) \\
r_2 &= \frac{1}{m}(R_U + f_T(n_m, \theta_m, (1-w).U_m).(1-t_T)) \\
&\quad -\frac{dU_m}{dt} \\
r_3 &= \frac{d^2 n_m}{dt^2} + \frac{df_Q(n_m, \theta_m, (1-w).U_m)}{I_m dt} \\
&\quad + \frac{f_Q(n_m, \theta_m, (1-w).U_m)}{I_m \tau_c} - \frac{k_y Y_m}{I_m\, \tau_c} + \frac{dn_m}{\tau_c dt}
\end{aligned}$$

where f_T, f_Q, and R_U represent three different tables. t_T is the deduction factor.
A summary of evaluation form for the abovemen-

tioned residuals are given bellow:

$$
\begin{aligned}
r_1 &= \frac{d\Delta\theta_m}{dt} + k_t\Delta\theta_m + \Delta\dot{\theta}_{inc} \\
r_2 &= F_T(\Delta n_m, \Delta\theta_m, w, t_T) \\
r_3 &= F_Q(\Delta n_m, \Delta\theta_m, w, \Delta k_y)
\end{aligned}
$$

Using the evaluation form one can obtain the expression of the sensitivity of each residual to each fault by taking partial derivatives w.r.t. the considered variables or parameters. However, because of the tables (functions f_{12} and f_{13}), indicated by unknown numerical functions F_T and F_Q, these sensitivities can't be calculated for the residuals b) and c). Only simulation tests can be performed to evaluate these. The evaluation procedure leads to the construction of a signature table, which in turn can be used to isolate different faults.

4 Simulation Results

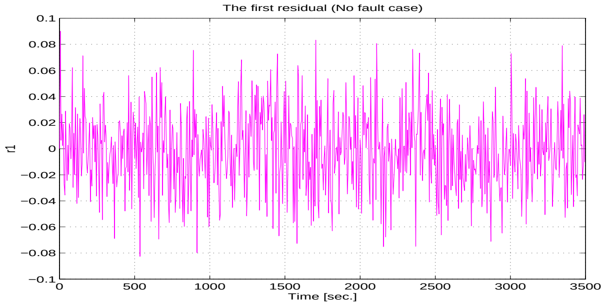
The residuals can be calculated by using the tables directly. For computing the differential terms in the expressions Euler method has been applied. The resulting residuals for the non-faulty case are shown in figure 5.

The third residual shows significant variations in both its mean value and its variance. This is mainly due to existence of the term involving numerical differentiation of one of the tables output (f_{12}). For each set of inputs, the output is calculated by interpolating between the tables real data. This introduces some calculation error which again is magnified due to numerical calculation of the differential term. Special care should, hence, be taken in the decision algorithms.

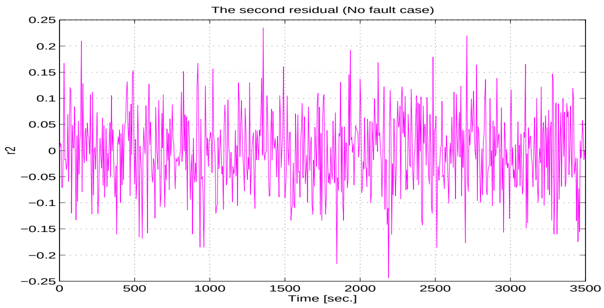
The impact of the defined faults is illustrated in figure 6. Big magnitude for sensor faults are chosen mainly for demonstration purpose. However, they are realistic enough as they represent the critical cases for the system.

Observing the first residual, 6(a), the impact of the sensor faults is evident. On the other side, the incipient fault is too small to have a visual effect on the residual. However, using an appropriate FDI procedure, it is possible to detect it [10]. Since the impact of the faults on the second residual (dashed lines), shown in figure 6(b), is not quite visible, a filtered version (solid lines) of this residual is also presented. The (low-pass) filter has following dynamics: $H(s) = \frac{0.05}{s+0.05}$.

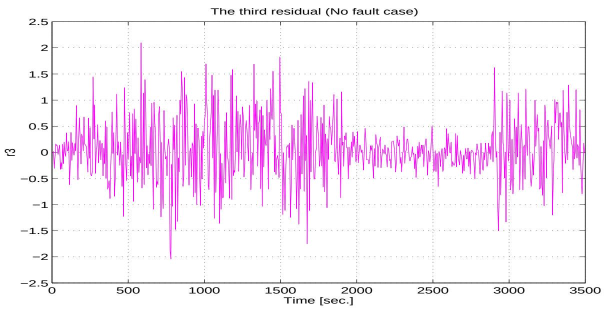
In general, all residuals are affected by the faults defined by their evaluation form. It is possible to detect all introduced faults by applying appropriate FD algorithms. Some preliminary results can be found in [10].



(a) The first residual r_1



(b) The second residual r_2



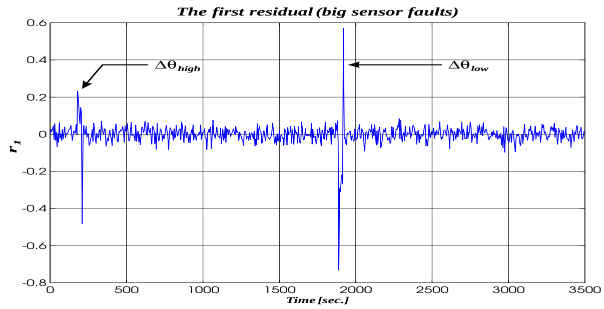
(c) The third residual r_3

Fig. 5. Obtained residuals for non-faulty case

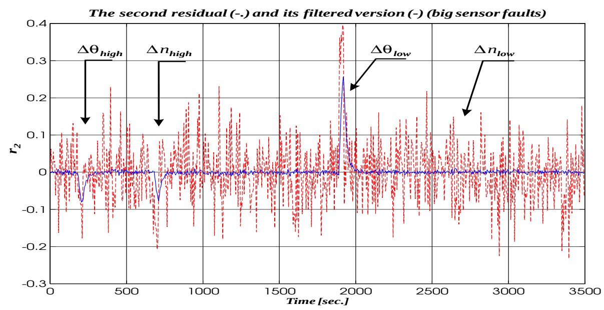
5 Conclusion

The structural approach is presented and is applied to the ship propulsion benchmark proposed in Safeprocess97. Well-defined digraph theory is employed in this approach which allows developing a software tool that can fully support design engineers. One of the main advantages of this approach is that even course information available on the system (qualitative, quantitative, rules) can be used during all the design phases. Detailed informations are, hence, not necessary to find the monitorable part (over-determined part) of the system. However, this information is needed to compute the residuals (ARRs).

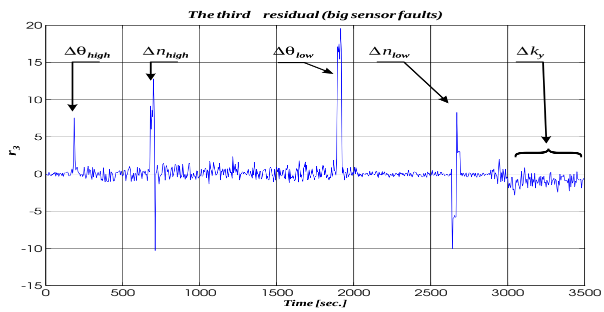
Simulation results show that all defined faults can be detected.



(a) The first residual r_1



(b) The second residual r_2



(c) The third residual r_3

Fig. 6. Obtained residuals for the faulty case (big sensor faults)

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