A NOVEL APPROACH TO SENSOR FAULT DETECTION AND ISOLATION IN AUTOMOTIVE SYSTEMS

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Abstract: A technique for the systematic design of fault-tolerant automatic measurement systems was proposed by the authors in a previous paper. It is based on the use of "analytical redundancy" relationships concerning both the measurement system and the monitored devices. In this paper, the technique was applied to the handling of sensors and actuators used for the electronic control of internal combustion engines. This represents the preliminary step toward the realisation of a fault tolerant measurement and control system for the automotive systems. The paper describes in detail the realised diagnostic scheme and its performance evaluated on a number of simulated and real tests carried out in normal and faulty operating conditions. The considered test bed allowed the proposed approach to be characterised in terms of fault sensitivity and selectivity.

Keywords: automotive engine, sensor fault location, fault tolerant systems, automatic measurement station.

1   INTRODUCTION

An increasing number of sensors and actuators is currently employed in automotive systems [1]. In fact, the correct operating of modern electronically controlled engines is based on a number of measurement information (*e.g.* velocity and position of the crankshaft, inlet manifold pressure, inlet manifold air and coolant temperatures, battery voltage, throttle position). In addition, the increasing demand of security and comfort pushes toward an increasing use of suitable sensors and actuators. The antilock braking system and anti-spin traction control are now used in almost every vehicle. Environmental sensors are used not only for measuring and optimising the in-vehicle conditions, but also for evaluating the outside conditions (presence of ice, intensity of rain, road characteristics, visibility) and for controlling the exhaust gas emissions. Anti-crash sensors and GPS are further sensor systems set up to improve the security and comfort of modern automotive systems. The driver status is also planned to be on-line monitored by more complex measurement systems that are aimed to reduce the number of crashes due to human errors.

This means that like in nuclear plants, aircraft, space vehicles, and chemical processes the automotive measurement system must be strongly fault tolerant [2]-[3]. Hardware and/or software schemes that perform the tasks of failure detection, isolation, and accommodation on the automatic measurement and control system (IFDIA schemes) are then increasingly required [4]. Several approaches has been reported to detect and isolate either sensor or actuator failures, with particular reference to automotive engines [5]-[8]. Their successful implementation demonstrates that IFDIA schemes are even more applicable in automotive at least than in aerospace systems, since automotive systems generally present significantly lower constraints on the required detection rates due to the relatively slow dynamics involved. In particular, the solution proposed in [7] is very promising as concern fault sensitivity and selectivity even if the required computational power seems hardly compatible with an on-board implementation.

Authors experienced a set of different solutions to the IFDI problem all based on the analytical redundancy relation approach [9]-[12]. Several software implementations were explored, based on Artificial Neural Network and Expert Systems. The obtained IFDI schemes were successfully set up and tested on large size and complex measurement and control systems. Moreover, the authors developed a technique for the systematic design of fault-tolerant automatic measurement systems based on analytical redundancy relation IFDIA schemes [13]. The proposed technique suggests either the number and location of the sensors to be used in measurement systems to be designed or the modifications needed in an existing measurement system for satisfying user requirements. Finally, it helps the designer in the practical implementation of the IFDIA scheme, by identifying the required analytical redundancy relationships.

After a brief recall of the proposed design approach, this paper deals with the design of an IFDIA

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scheme, based on the set of sensors usually adopted for the handling of electronically controlled engines. It was suitably realised to be integrated with the engine control software. This represents a first nucleus of a fault-tolerant automatic measurement system dedicated to the handling of automotive systems.

2   THE MEASUREMENT SYSTEM DESIGN TECHNIQUE

The first information a measurement system designer needs concerns the characteristics of the system under test and the physical quantities to be measured. Then, specifications about the expected IFDIA features have to be defined mainly in terms of quantities on which such features are required:

- physical quantities to be measured, S_i i=1,N_S;
- physical quantities on which a fault detection, isolation, accommodation capabilities are required.

A general criteria that must drive designer choices is searching for the maximum system reliability with a total amount of hardware not greater than that required by a total physical redundancy scheme (three sensors for each quantity on which IFDIA features are requested).

Some analytical and graphical tools [13]-[15] are the basis of a software tool developed by the authors. It interacts with the designer by requiring data and choices, and provides the sensors to be installed and the relationship to be implemented. In addition, it estimates the value of parameters, which quantify the IFDIA features obtained and the amount of the hardware necessary for implementing the features themselves.

The proposed procedure, described in detail in [13] is briefly recalled in the following.

1) Representation of all the available knowledge about the system in terms of relations (R_i) among measurable quantities (Q_i).
2) Building of the Redundancy Graph (RG) and its inverse (IRG), namely graphs representing Q_i as vertex (V) and the relations among them as edges (E) or vice versa.
3) Computation of $E/V(Q_i)$ and of $E/V(R_i)$, starting from RG and IRG, respectively.
4) For each quantity to be measured S_i and by using the IRG, definition of sets $_i$ of the relations in which the specific sensor S_i is included.
5) For each set $_i$ and by using $E/V(R_i)$ values, selection of the relations (one or two) characterised by:
   a) the lowest values of E/V,
   b) the minimum number of sensor involved,
   c) the higher validity level, computed as $VL(S_i) = 2 \cdot E/V(S_i) + 1$,
   which then form a general relation set
6) Definition of the set   of the N sensors involved in the relations included in   .
7) By using the IRG, inclusion in   of further relations including only sensors already in   ; this activity increases the IFDI capabilities without adding any additional sensor.
8) On the basis of relations in   , drawing of the Sensor Redundancy Graph (SRG), of its inverse ISRG and computation of the related $E/V(S_i)$, $E/V(R_i)$ values.
9) On the basis of $E/V(S_i)$ values, computation of the $VL(S_i)$;
10) Determining for each one of the considered sensors the possibility of detection, isolation and/or accommodation as follows:
   a) if $VL(S_i) > 1$, the IFDIA is always possible on S_i;
   b) if $VL(S_i) = 1$ but the product between the $E/V(S)$ values of the sensors included in its only relationships   0, the IFDIA is still possible, since the considered sensor is the only one with $LV(S) = 1$ in the relationship;
   and evaluation of sum of the sensors satisfying conditions a) and b) above, N_A.
11) Computation of two global index representative of the obtained IFDIA scheme:
   - *percent redundancy degree*, $PRD = (1$-N_S/N) 100, which gives a measure of the resulting hardware redundancy;
   - *percent fault accommodation degree*, $PFAD = N_A/N$, which gives a measure of the accommodation capability of the system.

The first index allows the obtained IFDIA scheme to be compared with other possible solutions. The second index, together with $VL(S_i)$ values, constitutes a useful mean of analysis of the behaviour of the measurement system after a sensor fault. As an example, a *PFAD* equal to 100 means that every sensor fault can be accommodated.

The designer may run more times this procedure, operating changes to previous choices, until the two aforementioned parameters assume values that respect criteria enounced at start.

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3   FAULT DETECTION, ISOLATION, AND ACCOMMODATION IN AN AUTOMOTIVE ENGINE

3.1   The engine under test

As far as the characteristics of the system under test are concerned, it is the four-cylinder spark ignition engine 2000cc, 16 valves (by FIAT), schematised in Fig. 1. The IFDI scheme has been designed for an engine control system based on a microprocessor unit, which controls the fuel ignition through the measurement of some engine characteristics: throttle position, inlet manifold pressure, detonation, inlet manifold temperature, engine speed, and so on.

3.2   Design of the fault tolerant measurement system

The procedure described in the previous section was applied. The considered measurable quantities are throttle position (thr), inlet manifold pressure (p_{man}), crankshaft speed (rpm), inlet manifold temperature (T_{man}), and air mass flow in the motor $\left(\overset{\bullet}{m_a}\right)_{eng}$. These quantities will be referred in the following as $Q1$-$Q5$, whereas the corresponding sensors will be referred as $S1$-$S5$.
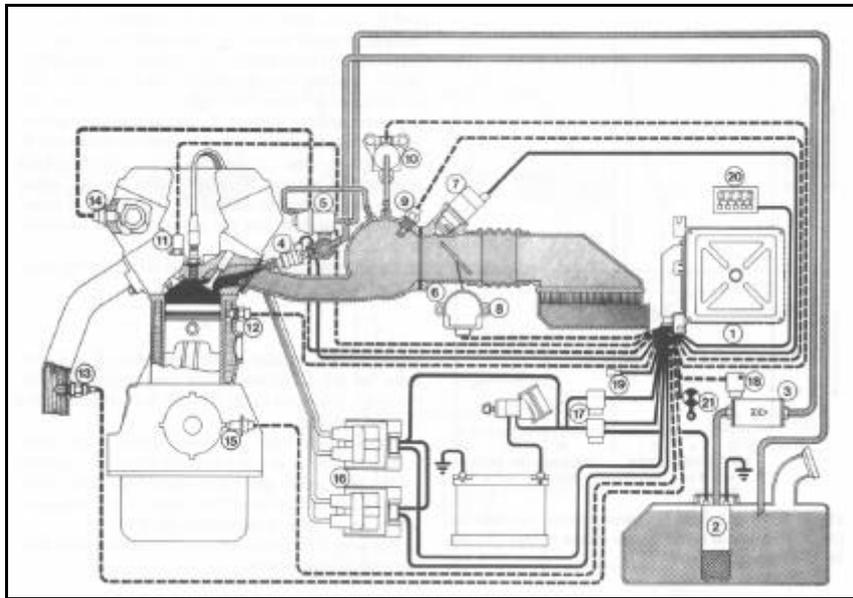
The available knowledge on the system consists in a number of relations obtainable as described in the following.

The *filling-emptying* equation states:

$$\frac{\partial p_{man}}{\partial t} = \left[\left(\overset{\bullet}{m_a}\right)_{thr} - \left(\overset{\bullet}{m_a}\right)_{eng}\right] \cdot \frac{R_{air}T_{man}}{V_{man}} \quad , \tag{1}$$

where $\left(\overset{\bullet}{m_a}\right)_{thr}$ is the air mass flow in the manifold, R_{air} is the gas constant, and V_{man} is the manifold volume. Being

$$\left(\overset{\bullet}{m_a}\right)_{thr} = f_1(p_{man},thr) \quad , \tag{2}$$

Figure 1. Schematisation of the considered engine.

[1] microprocessor based control unit; [2] fuel pump; [3] fuel filter; [4] injectors; [5] fuel pressure regulator; [6] throttle; [7] minimum valve control; [8] throttle potentiometer; [9] inlet manifold temperature sensor; [10] inlet manifold pressure sensor; [11] detonation sensor; [12] coolant liquid temperature sensor; [13] oxygen in the exhaust gas sensor; [14] timer; [15] engine speed sensor; [16] ignition distributors; [17] signal samplers; [18] trimmer; [19] diagnostic connectors; [20] trip computer; [21] malfunctioning indicator.

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equation (1) can be written as:

$$\frac{\partial Q2}{\partial t} = [f_1(Q2, Q1) - Q5] \cdot K_1 \cdot Q4 \qquad (3)$$

Starting from the equation for the computation of the crankshaft torque:

$$\frac{2\pi}{60} \cdot \frac{\partial rpm}{\partial t} = \frac{T_{ENG} - T_A - T_R}{I_{ENG}} \qquad (4)$$

where T_{ENG} is the engine torque, T_A is the aerodynamic resistant torque, T_R is the friction torque, I_{ENG} is the engine inertia. Being

$$T_{ENG} = a_0 + a_1 \cdot \left(\overset{\bullet}{m_a}\right)_{eng} + b_1 \cdot afr + b_2 \cdot (afr)^2 + c_1(sprk) + c_2(sprk)^2 + d_1 \cdot rpm$$

$$+ d_2 \cdot (rpm)^2 + e_1(sprk)rpm + +e_2(sprk) \cdot \left(\overset{\bullet}{m_a}\right)_{eng} + e_3(sprk)^2 \cdot \left(\overset{\bullet}{m_a}\right)_{eng} \qquad (5)$$

$$sprk = \text{ignition spark timing} = f_2(p_{man}, rpm) \qquad (6)$$

$afr = $ air/fuel ratio, supposed constant and equal to the required one

$$T_A = K_2 \cdot (rpm)^2 \qquad (7)$$
$$T_R = K_3 \qquad (8)$$
$$I_R = K_4 \qquad (9)$$

equation (4) becomes:

$$\frac{2\pi}{60} \cdot \frac{\partial Q3}{\partial t} = \frac{f_3(Q2, Q3, Q5) - K_2 \cdot Q3^2 - K_3}{K_4} \qquad (10)$$

Moreover, it is possible to write:

$$\left(\overset{\bullet}{m_a}\right)_{eng} = f_4(p_{man}, rpm) \cdot rpm \quad \text{and in other terms:}$$

$$Q5 = f_4(Q2, Q3) \cdot Q3 \qquad (11)$$

A further temporary redundancy relationship can be derived starting from the equations of the fluidodynamics of the fuel, of the fuel to be injected, and of the considering the definition of the air/fuel ratio:

$$Q5 = K_5 \int_0^t [K_6 \cdot Q5 + K_7] dt + K_8 \qquad (12)$$

The functions f_1-f_4 introduced in the above equations are tabled whereas the constants K_1-K_8 are obtained from suitable regressions on data coming from characterisation tests carried out on the specific engine under analysis.

Summarising the relationships synthesising the knowledge on the system are (3), (10), (11), and (12). They will be referred in the following as *R1-R4*, respectively.
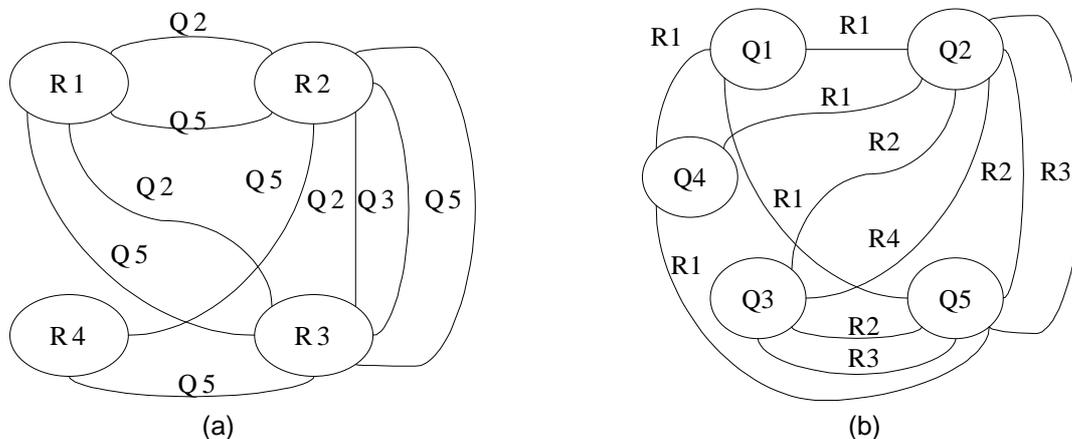

Figure 2. Redundancy Graph (a) and Inverse Redundancy Graph (b) of the system under analysis.

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Tab. I. Meaningful parameters of RG

Quantity	# edge	# vertex	E/V	VL
Q1	0	0	0/0	0
Q2	3	3	1	3
Q3	1	2	0.5	2
Q4	0	0	0/0	0
Q5	6	4	1.5	4

Tab. II. Meaningful parameters of IRG

Relation	# edge	# vertex	E/V
R1	3	3	1
R2	3	3	1
R3	3	3	1
R4	0	1	0

RG and IRG corresponding to the above relations and quantities are reported in Fig. 2a and 2b respectively, whereas the related meaningful parameters are reported in Table I and II.

The quantities indispensable for engine control, available in most commercial vehicles, are *Q1*, *Q2*, and *Q3*. They were then chosen as quantities to be measured *S1-S3*. The measurement of *Q4* and *Q5* certainly would increase the IFDI scheme reliability. Nevertheless, it was decided to design and measurement system characterised by the minimum hardware redundancy (minimum *PRD* value) in order to permit an easy on-board implementation. In this hypothesis, it is useful to substitute *R3* in all the other relations, obtaining *R1'*, *R2'*, and *R4'*. The obtained SRG and ISRG are reported in Fig. 3a and 3b respectively, whereas the related meaningful parameters are reported in Table III and IV.

In this configuration, the detection, isolation and accommodation degrees are all equal to 100 % with a *PRD* of 0 %.

3.3   IFDIA scheme implementation

The first step for the IFDIA scheme implementation is the residual generation. For each relationship R_i, the corresponding residual r_i was defined as (A-B)/A where A and B are the two members of each relation. In order to analyse these residuals, a simulation model of the engine was set up in Matlab[TM] environment. In particular a Simulink[TM] implementation of the above stated equation was used to produce measurand values. Sensor outputs in unfaulty conditions were obtained by corrupting measurand values with acquisition and quantization noise. The following faults were simulated on each sensor: short circuit, SC, by setting the sensor output to zero, open circuit, OC, by setting the sensor value to full scale), hold, by the sensor output equal to the last unfaulty value. Also these faulty values were corrupted by suitable measurement noise. Table V synthesises the range of residual variations in all the considered faulty and unfaulty statuses, obtained over a meaningful number of operating conditions. It is important to note that the residual have noticeable variations also in unfaulty conditions. This is due to the uncertainties of the model and of the estimated constants *K1-K8*, on the basis of steady-state conditions.

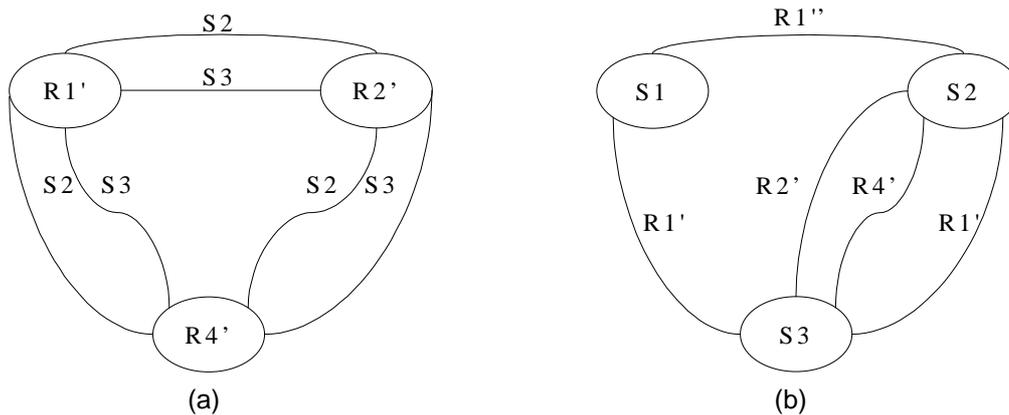(a)   (b)

Figure 3. Sensor redundancy graph (a) and Inverse sensor redundancy graph (b) of the considered IFDIA scheme.

Tab. III. Meaningful parameters of SRG

Sensor	# edge	# vertex	E/V	VL
S1	0	0	0	1
S2	3	3	1	3
S3	3	3	1	3

Tab. IV. Meaningful parameters of ISRG

Relation	# edge	# vertex	E/V
R'1	3	3	1
R'2	1	2	0.5
R'4	1	2	0.5

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Tab. V Residual variations in all the considered faulty and unfaulty conditions

	r1'max	r1'min	r2'max	r2'min	r4'max	r4'min
Unfaulty	0.00E+00	-1.22E+00	2.09E-16	-2.08E-16	1.02E+00	0.00E+00
thr=OC	1.95E+02	-1.97E+02	2.09E-16	-2.08E-16	1.02E+00	0.00E+00
thr=SC	7.60E-01	-2.97E+00	2.09E-16	-2.08E-16	1.02E+00	0.00E+00
thr=hold	8.35E-02	-2.30E+00	2.09E-16	-2.08E-16	1.02E+00	0.00E+00
p_{man}=OC	0.00E+00	-1.22E+00	2.99E-16	-2.00E-16	1.09E+00	0.00E+00
p_{man}=SC	0.00E+00	-1.22E+00	2.39E-16	-2.13E-16	1.99E+02	-6.45E+01
p_{man}=hold	0.00E+00	-6.40E+00	2.21E-16	-2.25E-16	4.37E+01	-1.40E+04
rpm=OC	0.00E+00	-1.22E+00	1.85E-16	-2.81E-16	1.02E+00	0.00E+00
rpm=SC	0.00E+00	-1.22E+00	2.40E-16	-2.15E-16	1.02E+00	0.00E+00
rpm=hold	0.00E+00	-8.11E+00	2.06E-16	-2.00E-16	1.02E+00	0.00E+00

Nevertheless, the unfaulty examples allow suitable thresholds to be identified for each residual. The fault detection is obtained by comparing these thresholds with the actual residual. In order to identify the fault a small size rule-based Expert System was realised.

3.4   IFDIA performance evaluation

The IFDIA scheme performance was first verified in simulation tests. They were obtained with reference to typical operating cycles of the engine during which the different faults were introduced. The resulting diagnostic performance is synthesised in Table VI. The impossibility of detecting some faults (OC and hold) on the throttle sensor are due to the its presence in only one relation. However, it has to be noted that the main task of the engine control (determining the ignition time) is carried out by elaborating only p_{man} and *rpm* values.

A further test set consisting in 342 different real operating conditions was used for further verifying the system performance. Data are obtained by an acquisition unit by Magneti Marelli, employed for engine analysis purposes. Fig. 4 reports the values of the residual *r1'* in all the considered real unfaulty operating conditions and having produced a SC fault on the throttle sensor.

4   CONCLUSIONS

The paper applies a novel technique for the design of fault tolerant measurement systems to the automotive field. A first nucleus concerning the measurement system dedicated to the engine control was designed and tested. The experimental tests carried out both in simulated and real environment show good diagnostic performance with absence of missed detection.

The fault accommodation capability is still low for the characteristics of the used relationship, characterised by high residuals also in absence of faults.

The small dimension of the set up scheme (3 sensors and 3 relationship) allows an on-line on-board implementation.

ACKNOWLEDGEMENTS

Tab. VI. Diagnostic performance of the proposed IFDI scheme

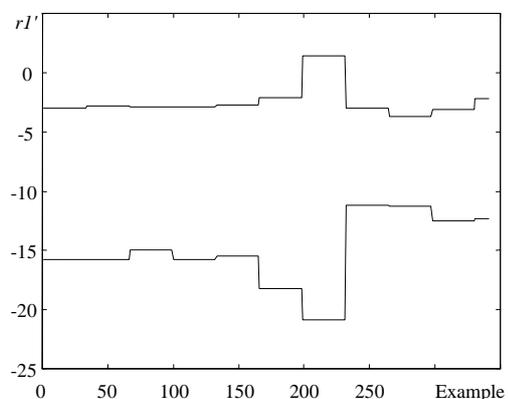|	*thr*	p_{man}	*rpm*
Correct Detection, Correct Location	34 %	100 %	100 %
Correct Detection, Incorrect Location	0 %	0 %	0 %
Missed Detection	66 %	0.0 %	0 %

Figure 4. Residual *r1'* for all the unfaulty (------) and *thr* = SC (——) real examples.

REFERENCES

[1] M.H. Westbrook, J.D. Turner, *Automotive sensors*, Institute of Physics Publishing, Bristol, 1994, 253 p.

[2] A.D. Pouliezos, G.S. Stravrakakis, *Real Time Fault Monitoring of Industrial Processes*, Kluwer Academic Publishers, Boston, 1994, 542 p.

[3] R.J. Patton, P.M. Frank, R.N. Clark, *Fault diagnosis in dynamic system theory and application*, Prentice-Hall International, 1989, 602 p.

[4] G. Betta, A. Pietrosanto, Instrument fault detection and isolation: state of the art and new research trends, *IEEE Transaction on Instrumentation and Measurement,* 49 (1) (2000).

[5] P.S. Min, Diagnosis of on-board sensors in internal combustion (IC) engines, in *Proceedings of 38th IEEE Vehicular Technology Conference*, 1988, pp. 229-236.

[6] P.S. Min, W.B. Ribbens, A vector space solution to incipient sensor failure detection with applications to automotive environments, *IEEE Trans on Vehicular Technology*, 38 (1989), 148-158.

[7] G. Rizzoni, P.S. Min, Detection of sensor failures in automotive engines, *IEEE Trans on Vehicular Technology*, 40 (1991), 487-500.

[8] P. Hsu, K. Lin, L. Shen, Diagnosis of multiple sensor and actuator failures in automotive engines, *IEEE Trans on Vehicular Technology*, 44 (1995), 779-789.

[9] G. Betta, A. Bernieri, A. Pietrosanto, C. Sansone, A neural network approach to instrument fault detection and isolation, *IEEE Transaction on Instrumentation and Measurement*, **44** (1995), 747-750.

[10] G. Betta, M. D'Apuzzo, A. Pietrosanto, A knowledge-based approach to instrument fault detection and isolation, *IEEE Transactions on Instrumentation and Measurement*, **44** (1995), 1009-1016.

[11] G. Betta, C. Liguori, A. Pietrosanto: "An Advanced Neural Network Based Instrument Fault Detection and Isolation Scheme", *IEEE Transactions on Instrumentation and Measurement*, **47** (2) (1998), 507-512.

[12] G. Betta, C. Liguori, A. Pietrosanto, Comparison between IFDI schemes based on expert systems and neural networks, *IEEE Transactions on Instrumentation and Measurement*, **47** (5) (1998), 1106-111.

[13] G. Betta, C. Liguori, A. Pietrosanto: "Instrument Fault Location and Accommodation in Automatic Measurement Stations", in *Proceedings of* XV IMEKO World Congress, 1999, vol. VIII, pp 21-26.

[14] S.C. Lee, Sensor value validation based on systematic exploration of the sensor redundancy for fault diagnosis KBS, *IEEE Transactions on Systems, Man, and Cybernetics*, **24** (4) (1994) 594-605.

[15] S.C. Lee, Utilization of the sensor relationships in space power distribution system operations, *IEEE Transactions on Power Delivery*, **9** (3) (1994) 1267-1275.

[16] P.M. Frank, Fault diagnosis in dynamic system using analytical and knowledge-based redundancy. A survey and some new results, *Automatica*, **26** (1990), 459-474.

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