Analytical Redundancy for Sensor Fault Isolation and Accommodation in Public Transportation Vehicles

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***Abstract*—The paper discusses an instrument fault detection, isolation, and accommodation procedure for public transportation vehicles. After a brief introduction to the topic, the rule set implementing the procedure with reference to the kinds of sensors usually installed on public transportation vehicles is widely discussed. Particular attention is paid to the description of the rules aimed at allowing the vehicle to continue working regularly even after a sensor fault develops. Finally, both the estimated diagnostic and dynamic performances in the off-line processing of the data acquired in several drive tests are then analyzed and commented upon.**

***Index Terms*—Automotive systems, fault detection, fault diagnosis, instrument fault detection, isolation, and accommodation (IFDIA), sensor accommodation.**

I. INTRODUCTION

MANY currently innovative techniques for public transportation vehicle system management are based on the latest communication technologies such as GMS, UMTS, GPS, wireless Ethernet, and even short-range radios. Any of these can feature in public transportation vehicles equipped with mobile communication equipment to provide information about traffic and vehicle status to a central station. The aim is to allow the adaptive management of public transportation vehicle runs, of maintenance scheduling, and of fault repair through real-time centralized processing of data gathered from public transportation vehicles [1]–[3]. However, the efficiency and the usefulness of these integrated systems are of course dependent on the reliability of the information provided. Thus, the reliability of data sources must be evaluated and enhanced wherever possible. This problem is at the forefront for data concerning a number of fundamental bus functions such as antilock braking system (ABS), automatic door opening/closing, and automatic transmission systems that are based on signals from a wide set of sensors [4]. Hence, today, just like in aircraft or in space vehicle systems [5], [6], software for measurement system fault detection, isolation, and accommodation (IFDIA procedure) is required in motor vehicles too. Several approaches to the detection and isolation of either sensor or actuator failures have been developed in the past years with particular reference to automobile engines [7]–[10]. Their successful implementation demonstrated that IFDIA procedures can be used in these contexts, since automotive systems generally present significantly lower constraints on the required detection rates due to the relatively slow dynamics involved.

On the basis of previous experience in the field [11]–[18], in this paper the authors describe an analytical redundancy-based procedure designed for the onboard real-time fault isolation and accommodation of sensors typically mounted in public transportation vehicles. In particular, the outputs of ABS/antispin regulation (ASR), automatic gearshift, and engine sensors are preprocessed to be monitored. In the case of sensor fault detection, the fault alarms and diagnoses are rapidly transmitted to the central control station via General Packet Radio Service channel, and accommodated outputs are substituted for the faulty sensor outputs.

After an analytical and graphical description of the knowledge about the bus subsystems, the set of inference rules is reported. Then, the hardware and software architecture of the resulting IFDIA procedure is described in detail. The result of the application of rules to real signals, acquired in both fault and no-fault conditions, is shown; and finally the procedure performance is analyzed in terms of decision uncertainty, wrong isolations, missed detections, and accommodation accuracy.

II. THE SYSTEM UNDER ANALYSIS

The system under investigation was applied to a vehicle that is widespread in public transportation fleets, the IVECO EuroPolis (8060.45.5230 or 8360.46 V.4691), assembled by Cacciamali Engineering s.p.a. This bus is equipped with a high number of sensors located in different parts of the vehicle to ensure that the bus is operating correctly and that its runs are both comfortable and safe.

Only a number of the abovementioned sensors were selected to be monitored (listed in Table I), mainly those that are critical for both bus operation and passenger safety. They provide data for the onboard electronic control units as shown in Fig. 1. The CAN bus ensures that the unit communicates, thereby allowing data to be exchanged. In particular, the EGAS unit manages the engine fuel injection to ensure regular engine working, progressive acceleration, and low pollution emissions; and, amongst other sensors, it processes the engine angular speed (S_1). The automatic gearshift (ZF5HP590) is managed by a ZF control unit. It computes output signals of the input and output gearshift angular speed sensors (S_1, S_6, S_7) and, on the basis of the bus running conditions, automatically decides to change a gear. Finally, the WABCO unit provides the bus with its ABS and ASR. It avoids wheel slip, respectively, in the braking and acceleration phases by processing the output of the four toothed-wheel angular speed sensors (S_2, S_3, S_4, S_5).

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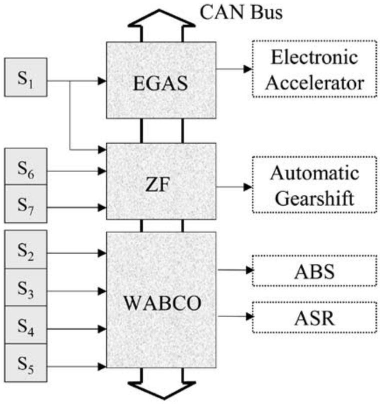


Fig. 1. The control units involved in the procedure.

TABLE I
LIST OF SELECTED SENSORS

S_1	Engine speed
S_2	Speed of the front right wheel
S_3	Speed of the front left wheel
S_4	Speed of the back right wheel
S_5	Speed of the back left wheel
S_6	Input gearshift speed
S_7	Output gearshift speed

All these sensors are based on the inductive sensing principle: the speed measurement is made by means of a pickup part consisting of a permanent magnet core coil placed close to a metal-toothed wheel. As the metal-toothed wheel spins, the magnetic field is altered: the output voltage rises as the tooth approaches the winding; it sharply drops to 0 V as the two components are aligned; and, finally, once the tooth passes the winding, a voltage in the opposite phase is produced. The measured quantity modulates the frequency of the output voltage, which has a sinewave waveform (Fig. 2). Its amplitude depends on several factors, such as:

1) wheel speed;
2) proximity of the wheel to the pickup;
3) strength of the magnetic field offered by the permanent magnet.

The frequency accuracy depends on the number of wheel teeth. The higher the number of teeth, the greater the accuracy. As regards faults, both peak voltage external to the output range and wrong frequency are symptoms of incorrect sensor operation.

III. IFDIA PROCEDURE DESIGN

Analytical redundancy allows automatic measurement systems to be featured with IFDIA capability if adequate knowledge about the system under test is available. In particular, the redundancy relation theory requires that as high as possible a number of relationships among the measured quantities be known. Once the rule set has been defined, the diagnostic capabilities of the procedure can be evaluated by means of the approach suggested in [19] and [20]. The sensor redundancy graph (SRG) and inverse sensor redundancy graph (ISRG) must be drawn to represent all the knowledge concerning the system and to allow the evaluation of some indexes that measure the IFDIA capability of the procedure.

1) The validity level of each sensor $\mathrm{VL}(S_i)$ is calculated on the basis of the SRG. The higher the $\mathrm{VL}(S_i)$, the higher the number of sensor faults after which the accommodation of S_i is still possible.
2) The degree of redundancy percentage $\mathrm{PRD}_{\%}$

$$\mathrm{PRD}_{\%} = \left[1 - \frac{\text{monitored quantities}}{\text{total number of sensors involved}}\right] \cdot 100. \quad (1)$$

3) The degree of isolation percentage $\mathrm{PFID}_{\%}$

$$\mathrm{PFID}_{\%} = \left[\frac{\text{number of sensors with } \mathrm{VL}(S) \neq 0}{\text{total number of sensors involved}}\right] \cdot 100. \quad (2)$$

4) The degree of fault accommodation percentage $\mathrm{PFAD}_{\%}$

$$\mathrm{PFAD}_{\%} = \left[\frac{\text{number of accomodable sensors}}{\text{total number of sensors involved}}\right] \cdot 100. \quad (3)$$

As regards the bus under test, 14 analytical relationships expressing knowledge about its traction, gears, and brakes were found. They are simple two member equations based on the measured quantities (wheels, gearshift, and engine angular speed) and can be grouped in the following subsets.

1) *Relationships between the wheel speed sensors*

$$R_1 : \frac{S_2}{S_3} = k_1(t)$$
$$R_2 : \frac{S_2}{S_4} = k_2(t)$$
$$R_3 : \frac{S_2}{S_5} = k_3(t)$$
$$R_4 : \frac{S_3}{S_4} = k_4(t)$$
$$R_5 : \frac{S_3}{S_5} = k_5(t)$$
$$R_6 : \frac{S_4}{S_5} = k_6(t).$$

$R_1 - R_3$ highlight the links between the angular speeds provided by the front right wheel sensor and the other three; similar relationships are written for the other wheels ($R_4 - R_6$).

2) *Relationships between the wheel and the gearshift speeds*

$$R_7 : \frac{S_2}{S_7} = k_7(t)$$
$$R_8 : \frac{S_3}{S_7} = k_8(t)$$
$$R_9 : \frac{S_4}{S_7} = k_9(t)$$
$$R_{10} : \frac{S_5}{S_7} = k_{10}(t)$$
$$R_{11} : S_7 = k_{11}(t) \cdot \frac{S_4 + S_5}{2}.$$

$R_7 - R_{10}$ express the mechanical bond between the gearshift and the wheel angular speed; R_{11} takes into account the presence of the differential transmission system on the rear axle.

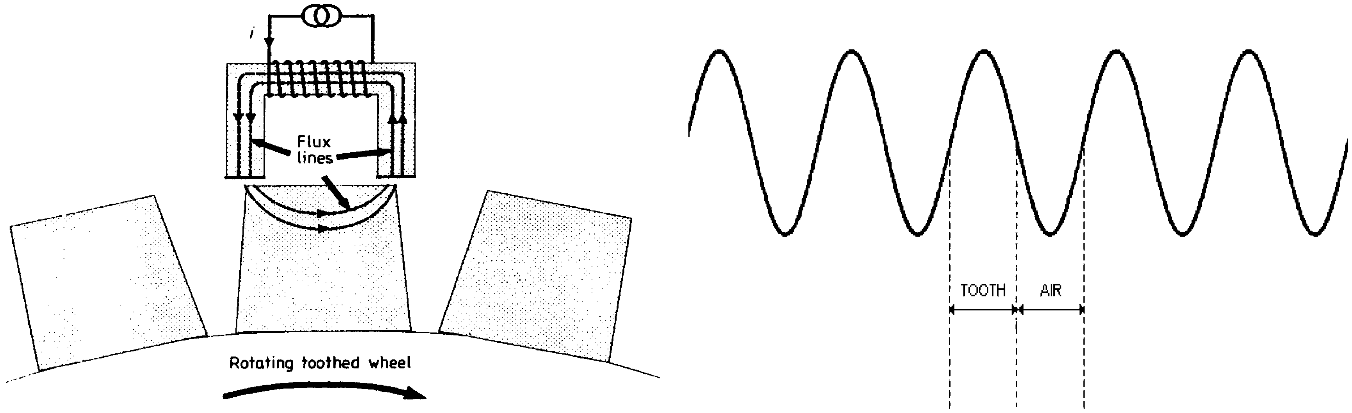
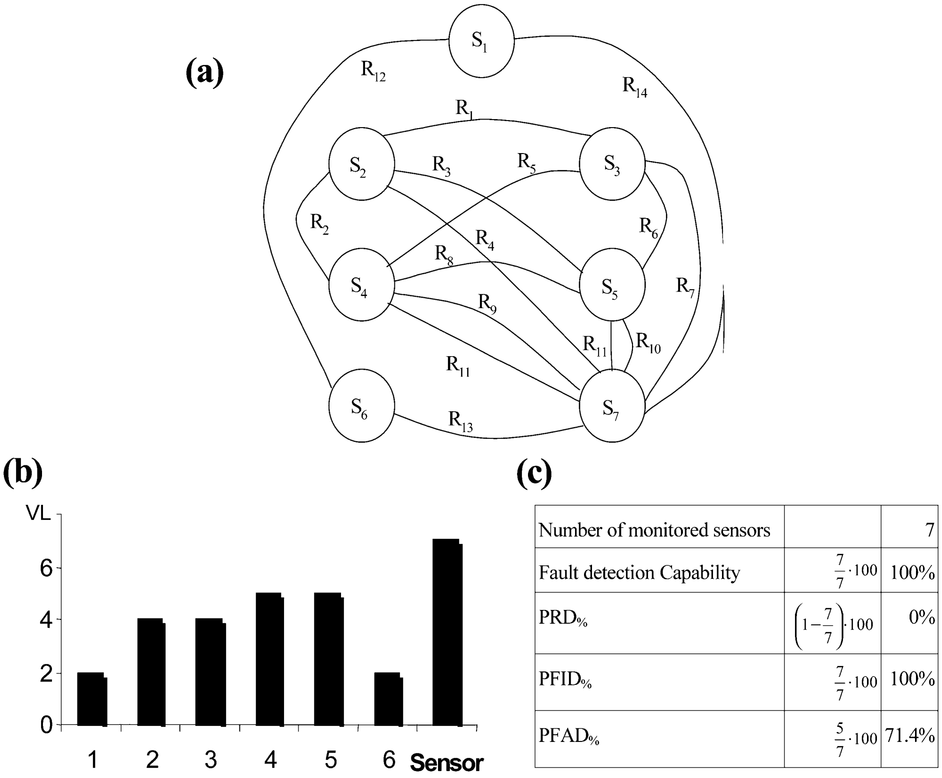


Fig. 2. Physical principle of the speed sensors.



Number of monitored sensors		7
Fault detection Capability	$\frac{7}{7}\cdot 100$	100%
PRD%	$\left(1-\frac{7}{7}\right)\cdot 100$	0%
PFID%	$\frac{7}{7}\cdot 100$	100%
PFAD%	$\frac{5}{7}\cdot 100$	71.4%

Fig. 3. (a) ISRG of the system, (b) validity level of the sensors under consideration, and (c) diagnostic performance indexes.

3) *Relationships between the engine and the gearshift speeds*

$$R_{12}: \frac{S_1}{S_6} = k_{12}(t)$$
$$R_{13}: \frac{S_1}{S_7} = k_{13}(t)$$
$$R_{14}: \frac{S_6}{S_7} = k_{14}(t).$$

R_{12} and R_{13} synthesize the mechanical bond between the engine and gear angular speed; whereas R_{14} takes into account the gear that has been inserted, with k_{14} assuming the following values according to the gear:

Gear	I	II	III	IV	V
K_{14}	3.43	2.01	1.42	1.00	0.83.

Fig. 3 shows the ISRG graph, the sensor validity levels (see [15] for more details on VL evaluation), and the previously seen indexes, for this set of relationships.

Since all the sensor validity levels are greater than one, faults occurring on all sensors of the measurement system can be detected, isolated, and accomodated without requiring any physical redundancy. Consequently, a PRD$_{\%}$ equal to 0%, and PFI$_{\%}$ and PFAD$_{\%}$ both equal to 100%, are obtained from the graphs, and these indexes prove that the number of analytical relationships available is sufficient to allow an efficient IFDIA procedure to be designed.

Nevertheless, some design choices should be made first of all to assure the maximum degree of safety. Even though it could be accommodated by the IFDIA procedure, a wheel angular speed sensor fault isolation should always cause the ABS/ASR system to be excluded, as well as generating a sudden warning. Moreover, dealing with a 2×4 vehicle with rear traction, the front wheels are bond-free, while the back wheels are tied together by the transmission differential system. This means that the angular speed of a front wheel can still not be predicted from the measurement of the other one. On the basis of all these considerations, it was preferred to require fault accommodation only for the back wheel sensors. Although this reduces the $\mathrm{PFAD}_{\%}$, since two sensors (front wheel angular speed) in the whole set cannot be accommodated, it does increase the overall reliability of the system as a whole.

Fig. 3(c) indicates the diagnostic indexes of the IFDIA procedure arising from these conclusions, namely, a $\mathrm{PRD}_{\%}$ of 0%, a $\mathrm{PFID}_{\%}$ of 100%, and a $\mathrm{PFAD}_{\%}$ of 71.4%.

Once the analytical relationships have been identified, the next step is for the most suitable "residual" generation technique to be chosen. The simplicity of the analytical relationships would seem to suggest that rule-based residuals be defined, thereby assuring promptness without reducing selectivity. In particular, some of the rules are based on the check values of k_i. Generally, the coefficients k_i, $(i = 1 \ldots 14)$, can assume different values depending on the running conditions of the bus and the measurement uncertainties of the quantities involved. However, in fault-free conditions their values are constrained in ranges defined by suitable thresholds

$$k_{thL}(R_i) \leq k_i \leq k_{thH}(R_i) \tag{4}$$

where $k_{thL}(R_i)$ and $k_{thH}(R_i)$, $(i = 1 \ldots 14)$, are the range extremities and can be evaluated in the experimental tuning phase.

A fault will be detected when some of the values of k_i are external to the range defined by (4). Then, analyzing the corresponding relationships and making use of suitable inferential rules, the fault that occurred can be isolated.

Moreover, in order to improve the promptness and the sensitivity of the procedure, further rules suggested by the sensor specifications were implemented. They require the peak sensor output voltages $V_{pk}(S_j)$, $(j = 1 \ldots 7)$, to be constrained in a range defined by suitable thresholds

$$V_{thL}(S_j) \leq V_{pk}(S_j) \leq V_{thH}(S_j) \tag{5}$$

where $V_{thL}(S_j)$ and $V_{thH}(S_j)$, $(j = 1 \ldots 7)$, are the sensor output voltage range extremities. They will be fixed in the tuning phase, also taking the measurement uncertainty into account.

As previously mentioned, the values assumed by $V_{pk}(S_j)$ depend on the bus running conditions. In particular, the higher the angular engine, wheel, or gearshift speeds, the higher the value of $V_{pk}(S_j)$. If a sensor peak voltage is external to the range defined by (5), an incipient fault warning can be provided.

IV. THE IFDIA PROCEDURE

The IFDIA procedure was implemented in LabVIEW (by National Instruments), because it allows easy management of the acquisition hardware without particular constraints for the diagnostic software. The algorithm, summarized in Fig. 4, ran continuously on an 800 MHz notebook PC and is subdivided into the following steps.

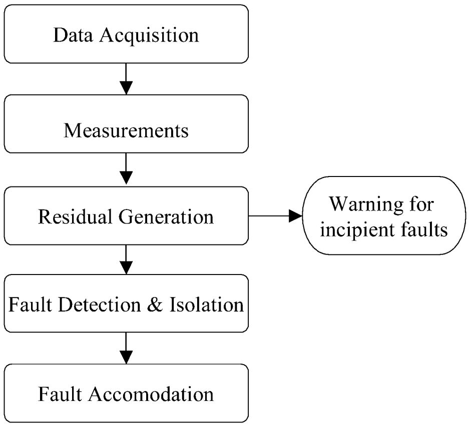


Fig. 4. The IFDIA procedure.

1) *Data acquisition:* In this phase the sensor outputs are acquired using a PCMCIA data acquisition board (12 bits, 8 A/D channels, 500 kHz maximum sampling frequency). A preliminary analysis of the sensor output signals allowed a 4 kHz maximum signal bandwidth to be estimated. Consequently, a 16 kHz sampling frequency was selected for each channel.
2) *Measurements:* The digital signal-processing module evaluates wheel, engine, and gearshift angular speeds together with the peak voltages of the sensor outputs. A new set of measurements is provided each second, by processing 16 000 samples for each sensor $(S_1 - S_7)$. The 1 s time interval was chosen in accordance with the typical operating rate of the electronic control units.
3) *Residuals generation:* The peak voltages $V_{pk}(S_j)$, $(j = 1 \ldots 7)$ and the coefficients k_i, $(i = 1 \ldots 14)$, are compared to the thresholds defined in (4) and (5), and a fault is probable when at least one of these thresholds is exceeded. In particular, if only $V_{pk}(S_j)$, $(j = 1 \ldots 7)$, exceeds the corresponding threshold, the warning for an incipient fault on sensor S_j is given. On the other hand, if some of k_i, $(i = 1 \ldots 14)$, are also external to the range defined by (4), further inferential rules, employed in the next step, must be triggered in order to ensure that a fault is present.
4) *Fault detection and isolation:* Faults are detected and isolated on the basis of rules of this type: IF all the relationships involving sensor S_j are not satisfied THEN a fault is detected and isolated on S_j. For example, if we consider the front right wheel speed sensor S_2, then all the relationships involving S_2 must not be satisfied for a fault to be detected and isolated, which in this specific case occurs when all the coefficients k_1, k_2, k_3, k_7 exceed the corresponding thresholds. Vice versa, if at least one of the relationships involving S_2 is satisfied (at least one of k_i does not exceed the corresponding thresholds), no fault will be detected and isolated. This operation logic contributes toward improving reliability and avoiding false alarms.
5) *Fault accommodation:* The accommodation section starts after a fault has been isolated; it accommodates faults by substituting the faulty sensor output with the expected output. The expected value can be achieved from each relationship including the faulty sensor, once the measured values of the other quantities involved are known. If more than one relationship is available, the expected value is

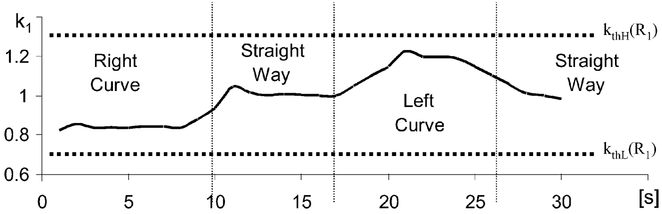


Fig. 5. Evolution of k_1 in different bus operating conditions.

calculated as a mean value of the values achieved by each redundancy relationship. As previously mentioned, faults occurring on sensors S_2 and S_3 are not accommodated. If, for example, we consider a fault occurring on the rear right wheel speed sensor (S_4) that is involved in five redundancy relationships R_2, R_4, R_6, R_9, and R_{11}, the expected value of S_4, S_4', is calculated as

$$S_4' = \frac{1}{5} \cdot \left[\frac{S_2}{\bar{k}_2} + \frac{S_3}{\bar{k}_4} + S_5 \cdot \bar{k}_6 + S_7 \cdot \bar{k}_9 + \left(2 \cdot \frac{S_7}{\bar{k}_{11}} - S_5 \right) \right] \tag{6}$$

where $\bar{k}_i$ is as follows:

$$\bar{k}_i = \frac{k_{thH}(R_i) - k_{thL}(R_i)}{2}. \tag{7}$$

V. TUNING OF THE IFDIA PROCEDURE

In order to achieve a reliable IFDIA procedure characterized by good sensitivity and response speeds and by low false-alarm rates, a careful definition of the thresholds involved in the procedure must be carried out.

In particular, the thresholds that define ranges (4) and (5) determine the sensitivity of the procedure: reduced ranges increase the probability of false alarms, whereas wide ranges decrease procedure sensitivity. In order to privilege the reliability of the procedure, thresholds were carefully chosen with the aim of assuring correct detections in all bus working conditions, thereby avoiding false alarms despite decreasing procedure sensitivity.

Thus, in order to test all the bus working conditions, the actual sensor output signals in fault-free conditions were initially analyzed in terms of signal-to-noise ratio, bandwidth, and amplitude. The trends of k_i, $(i = 1 \ldots 14)$, and of voltage amplitudes $V_{pk}(S_j)$, $(j = 1 \ldots 7)$, were measured and recorded. The corresponding thresholds were obtained by a statistical analysis of these trends, by imposing confidence levels higher than 95%.

Fig. 5 reports the evolution of k_1 for parts of a drive test including, respectively, a bend to the right, a straight section, and a bend to the left. It shows that the value of k_1 varies along the bus itinerary even in the absence of a sensor fault. In particular, for a bend to the right, k_1 assumes values lower than one because the left wheel spins faster than the right one, whereas for a bend to the left, wheel angular speed behavior is the opposite with k_1 assuming values greater than one. For a straight section both the wheel angular speeds are approximately the same and k_1 is thus close to one. In Fig. 5 the evolution of k_1 in different and limit working conditions is reported; as shown, k_1 ranges between 0.88 and 1.22 and therefore, thresholds $k_{thL}(R_1)$ equal to 0.70 and $k_{thH}(R_1)$ equal to 1.30 were fixed, because they assure a 100% confidence level.

The same criteria governed the statistical analysis of the signals acquired in different bus driving conditions to define the low and the high thresholds of the sensor output peak voltages. For example, in Fig. 6, the output signal of the front right wheel angular speed sensor is reported for two different speeds. It shows that in fault-free conditions, $V_{pk}(S_2)$ is within the range 0.10 V–4.00 V, and consequently, low and high thresholds equal to 0.05 and 5.00 V will assure the desired 100% confidence level.

VI. EXPERIMENTAL RESULTS

This section describes how the procedure was characterized in order to evaluate both its diagnostic and dynamic performances.

A. Diagnostic Performance

A number of tests were carried out to evaluate the performance of the proposed procedure in detecting, isolating, and accommodating sensor faults. Hence some sensor faults were suitably simulated in many different kinds of operating conditions (e.g., different speeds, modes of operation, and passenger loads). They were chosen among the most probable ones, and the mode of simulation for each sensor is indicated:

1) open circuit fault: by setting the sensor output voltage value to the full scale value, and adding Gaussian noise;
2) short circuit fault: by setting the sensor output voltage to zero value, and adding Gaussian noise.

Table II shows the results obtained; they confirm the good level of performance reached by the procedure. For short circuit faults there were, however, small percentages of missed detections (M.D.). These may occur at very low speeds in which at least one of the relationships containing the faulty sensor gives rise to residuals that do not exceed the fixed thresholds. It must be noted that the missed detection condition only persists until the vehicle speed increases; and, indeed, as soon as the speed increases, the residuals of the relationships containing the faulty sensor exceed the thresholds, thereby leading to fault identification. There is, therefore, only an acceptable delay in detecting the fault.

Further tests were carried out in order to evaluate the behavior of the procedure in the case of multiple faults, and simultaneous double faults, in particular, were simulated and tested.

Table III summarizes the performance achieved and highlights that correct detections and isolations are assured for double faults with similar percentages to single faults being obtained.

As regards accommodation, the performance was evaluated by comparing the expected and actual values of the accommodated sensor output. For example, in Fig. 7 the evolutions of the actual and calculated speed values are reported for the rear right wheel. They show that the difference is always constrained in a 5% range. Analogously, the accommodation accuracy for the other sensors was evaluated: a 10% range was obtained for the two gearshift speed sensors, whereas the worst performance was the 20% range obtained for the engine speed sensor. The latter can be mainly ascribed to the lower accuracy of the gear and engine speed measurements.

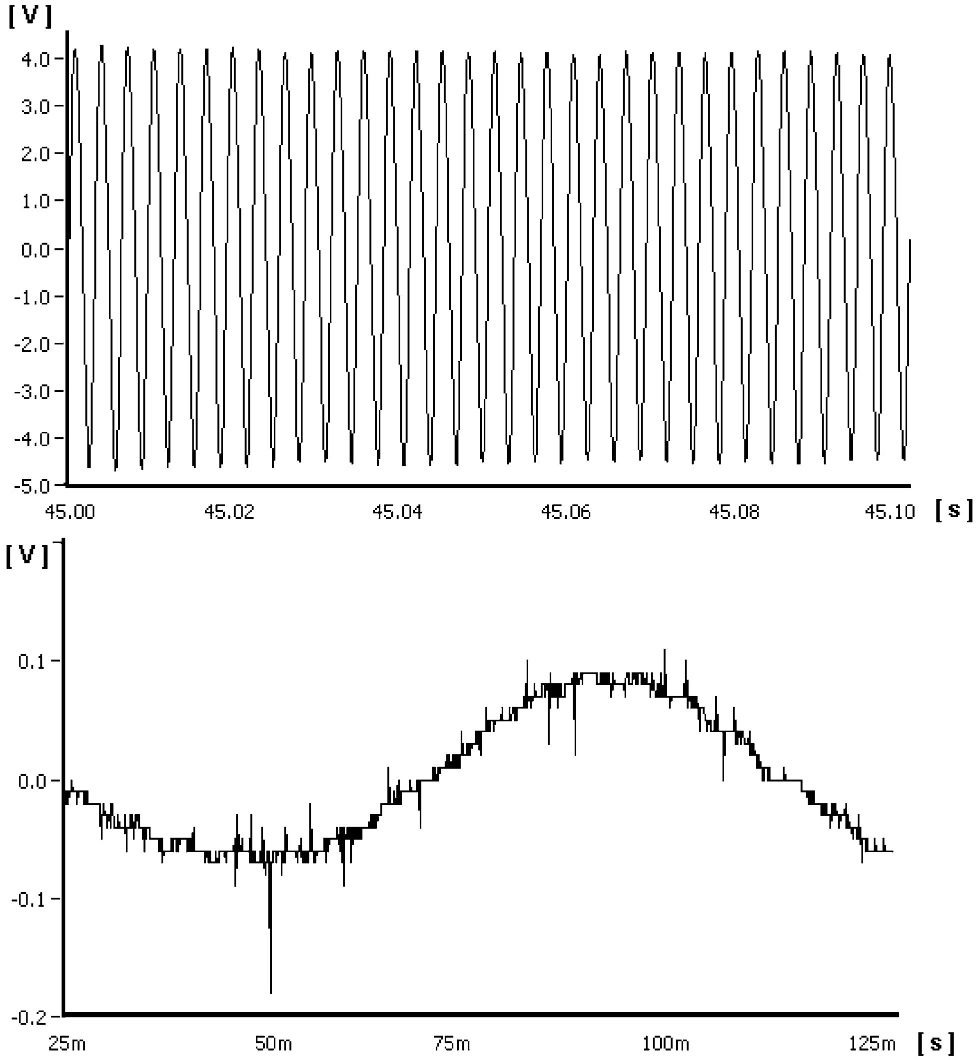


Fig. 6. S_2 output voltage versus time for two different angular speeds.

TABLE II
DIAGNOSTIC PERFORMANCE FOR DIFFERENT FAULTS (C.D. CORRECT DETECTION, M.D. MISSED LOCATION, C.L. CORRECT LOCATION, M.L. MISSED LOCATION, I.L. INCORRECT LOCATION)

FAULT TYPE	C.D.	M.D.	C.L.	M.L.	I.L.
S_1 OPEN	100%	0%	100%	0%	0%
S_1 SHORT	100%	0%	100%	0%	0%
S_2 OPEN	100%	0%	100%	0%	0%
S_2 SHORT	97%	3%	100%	0%	0%
S_3 OPEN	100%	0%	100%	0%	0%
S_3 SHORT	97%	3%	100%	0%	0%
S_4 OPEN	100%	0%	100%	0%	0%
S_4 SHORT	97%	3%	100%	0%	0%
S_5 OPEN	100%	0%	100%	0%	0%
S_5 SHORT	97%	3%	100%	0%	0%
S_6 OPEN	100%	0%	100%	0%	0%
S_6 SHORT	100%	0%	100%	0%	0%
S_7 OPEN	100%	0%	100%	0%	0%
S_7 SHORT	95%	5%	100%	0%	0%

TABLE III
DIAGNOSTIC PERFORMANCE FOR MULTIPLE FAULTS (C.D. CORRECT DETECTION, M.D. MISSED DETECTION, C.L. CORRECT LOCATION)

FAULTY SENSORS (X , Y)	C.D. SENSOR X	C.D. SENSOR Y	M.D. SENSOR X	M.D. SENSOR Y	C.L.
S_1, S_2	98%	100%	2%	0%	100%
S_1, S_6	100%	100%	0%	0%	100%
S_2, S_3	100%	100%	0%	0%	100%
S_3, S_4	100%	100%	0%	0%	100%
S_3, S_5	100%	100%	0%	0%	100%
S_4, S_7	95%	98%	5%	2%	100%

B. Dynamic Performance

A number of tests were carried out to evaluate the running times required by the procedure in different conditions of operation, such as no fault, fault detection and isolation, or fault accommodation. The IFDIA algorithm was run on a notebook 800 MHz processor PC and the following mean values were achieved:

1) no fault: 236 ms;
2) fault detection and isolation: 238 ms;
3) fault accommodation: 240 ms.

Since the typical working rate of the electronic control units is 1 Hz, the running times obtained prove that despite the use of less powerful computers the proposed procedure is suitable for onboard operation.

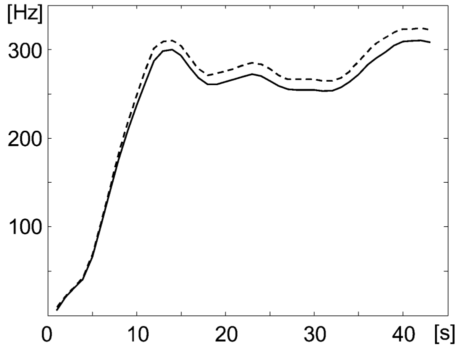


Fig. 7. Real (thin line) and accommodated (thick line) sensor output.

VII. CONCLUSIONS

An IFDIA procedure for public transportation vehicle sensors has been presented in this paper. Analytical redundancy relationships were implemented in simple inference rules to achieve real-time fault location on 100% of the sensors monitored. Accommodation is obtained for most of them (five of seven sensors), thereby improving the reliability of the whole vehicle. An implementation of the procedure on a commercial notebook PC required 238 ms to detect and locate a sensor fault and a further 240 ms for the accommodation. This performance is even better than required by the system dynamic and, finally, leads us to believe that it is suitable for onboard operation. Further developments will aim toward 1) extending the procedure to other sensors of the bus and 2) implementing it on the onboard control unit.

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