Health management system for the pantographs of tilting trains

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ABSTRACT

Tilting trains are provided with the ability of rotating their carbodies of several degrees with respect to the bogies about the longitudinal axis of the train. This permits a train to travel at a high speed while maintaining an acceptable passenger ride quality with respect to the lateral acceleration, and the consequent lateral force, received by the passengers when the train travels on a curved track at a speed in excess of the balance speed built into the curve geometry. When the carbody is tilted with respect to the bogie, the train pantograph needs to remain centered with respect to the overhead catenary, which is aligned with the track. The conventional solution is to mechanically link the pantograph to the bogie, but recent tilting trains have the pantograph connected to the carbody roof while a position servoloop continuously control the pantograph position such to keep it centered with the catenary. The merit of this design is to allow a gain of the useful volume inside the carbody. The pantograph position servoloop uses two position sensors providing a redundant position information to close the pantograph feedback loop and perform system monitoring.

The monitoring functions presently implemented in pantograph position controls are able to detect the servocontrol failures, but in case of conflicting information from the two position transducers they are not always able to sort out which of the two transducer is failed because some failures of the position transducers cannot be detected by simply looking at the output signals of the transducer. As a result, if a difference between the output signals of the two position transducers is detected, the tilting function is disabled and the train speed is reduced. Also, the entire pantograph is then removed and replaced because the functionality of each individual transducer can only be checked at shop level.

Developing better diagnostic techniques for the pantograph position control system have been encouraged by the train companies, but no work on this subject has so far been performed. A research activity was hence conducted by the Authors, that was aimed at developing an advanced diagnostic system that can both identify the presence of a failure and recognize which of the two position transducers is the failed one. In case of a transducer failure it is thus possible to isolate the failed transducer and keep the pantograph position control operational, thereby retaining the train tilting function. A further merit of the advanced diagnostic system is the reduction of maintenance time and costs because the failed transducer can be replaced without removing the entire pantograph from the train.

The general architecture of this innovative diagnostic system, the associated algorithms, the mathematical models for the system simulation and validation, the simulation results and the possible future developments of this health management system are presented in the paper.

1. THE PANTOGRAPHS OF TILTING TRAINS

Tilting trains perform carbody tilting towards curve's inner side, to reduce centrifugal force in curves at passengers' level and, therefore, to maintain a better or equivalent passenger comfort with respect to the lateral acceleration (and the consequent lateral force) on same curves' geometry at enhanced service speed (Figure 1). By tilting the carbody of a rail passenger vehicle relative to the track plane during curve negotiation, it is therefore possible to operate at speeds higher than might be acceptable to passengers in a non-tilting vehicle, and thus reduce overall trip time.

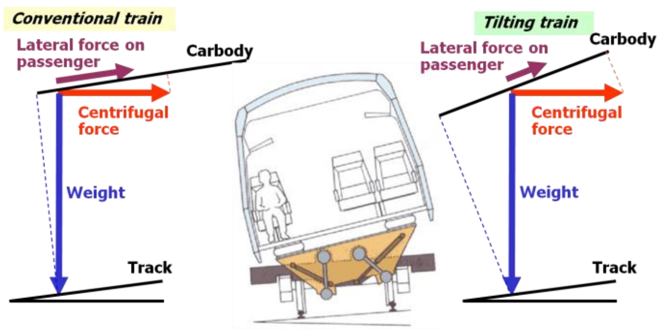

Figure 1. Tilting train concept

The recognized advantage of tilting trains is to increase the achievable service speed for passenger trains on existing tracks without being forced to invest very large sums of money to build a dedicated new track or to alter the geometry of the existing curves (Boon & Hayes, 1992). Both hydraulic and electromechanical actuation systems have been used to provide the controlled force necessary to tilt the carbodies of the train vehicles, though the majority of tilting trains in revenue service use hydraulic actuation systems.

A critical design issue associated with carbody tilting is the need to maintain the train pantograph centered with respect to the overhead catenary running at midpoint between the two track rails. Most tilting trains implemented the solution of rigidly connecting the pantograph structure to the bogie by means of a truss passing through the carbody. This is a simple design concept, but it reduces the useful volume within the carbody because enough empty space must be left around the vertical beams of the truss to accommodate carbody tilting. Most of the tilting trains developed in the last 10 years, however, used a different design in which the pantograph supporting structure is directly connected to the carbody roof while the pantograph itself can be moved relatively to its supporting structure in a direction opposite to the carbody tilting. By appropriately controlling the pantograph lateral position with respect to the carbody roof it is then possible to maintain the pantograph aligned with the catenary also when the carbody tilts. This is accomplished by an actuation system receiving the commands from the train electronics as outlined in the next section. The advantage of this solution is to allow a gain of useful space within the carbody.

The actuation technology used for the pantograph control of tilting trains following this design concept was the same as the carbody tilting system. The research activity presented in this paper was focused to the latest tilting train developed by Alstom (the so called: "Nuovo Pendolino") which makes use of hydraulic actuation, and the health management system developed in this research specifically refers to a hydraulically actuated pantograph control system. However, the same health management philosophy can be followed to develop effective diagnostic algorithms for an electrically actuated pantograph control system.

2. PANTOGRAPH POSITION CONTROL SYSTEM

The control of the lateral position of the pantograph with respect to the tilting carbody is performed by a closed loop system using two single-acting hydraulic actuators mounted as an opposite pair and controlled by an electrohydraulic servovalve (Figure 2). The pantograph is mounted on a carriage that can be moved along two tracks perpendicular to the longitudinal axis of the vehicle. The rod end of each of the two hydraulic actuators is connected to the carriage, while the head end is connected to a structure fixed to the carbody roof. Two springs mounted between the carriage and the frame maintain the pantograph centered in its mid position when the pantograph control system is not active.

Each of the two single-acting hydraulic actuators accepts the controlled flow from one of the two control ports of an electrohydraulic servovalve; therefore, the total of the servovalve and the two single-acting hydraulic actuators is equal to a hydraulic servocontrol comprised of a servovalve and a double-acting hydraulic actuator. The hydraulic power supply is provided by a constant pressure hydraulic power generation and control unit (HPGCU) located in the train vehicle undercarriage. The pantograph position command is generated by the train electronics simultaneously to the carbody tilt command as a function of the lateral acceleration, and a position servoloop is created for the pantograph in which the command is compared to the actual lateral position in order to close the position feedback loop. The servoloop position errors are processed by an appropriate control law that eventually generates the input signal to the flow control servovalve. The pantograph lateral position is measured by two position sensors, with each sensor placed inside one of the two hydraulic actuators.

The pantograph position control loop is single-hydraulic, dual-electrical and uses a single electrohydraulic servovalve with independent electrical coils accepting the control currents from the two independent control computers. Each computer interfaces with one of the two position sensors and mutually exchanges with the other computer the information of pantograph lateral position and servovalve current as well as the computer health status. Each computer thus generates an equal consolidated position feedback based on the average of the pantograph position sensors signals.

The control law (Figure 3) is based on a PID controller with a relatively low value of the integrator gain and a saturation on the integrator output. The function of the integrator is in fact to compensate for the steady state, or slow varying servovalve offsets, while the dynamic performance is dependent on the proportional and derivative gains of the control law.

A comparison of the signals of the two sensors is continuously performed during the train ride and if the difference between these signals is greater than a given threshold, an alert is generated and the tilting system operation is disabled. Both the carbody and the pantograph actuators are set in a bypass mode connecting the actuators lines to return. The tilting carbody recenters under its own weight while the pantograph recenters under the action of its springs. As the train tilting is disabled, the train speed is reduced to maintain an acceptable comfort level for the passengers and train safety, but with the consequence of a travel delay.

The rationale for disabling the train tilting in case of a discrepancy between the signals of the two position sensors of the pantograph is the concern of not always being able to detect the failure of each individual sensor. Failures such as a broken wire or a short circuit lead to an out of scale signal that can be easily detected, but other failures such as, for example, degradations originating variations of the sensors scale factor or increased offsets are failures cases that cannot be detected by the existing monitoring logics.

Therefore, it can well be that a difference between the signals of the two sensors is detected, but it is not possible to understand which of the two is the failed one. Moreover, in case the existing monitoring system recognizes and isolates the failed sensor, a risk exists that a subsequent failure of the remaining active sensor might go undetected, which could lead to a safety critical condition. The end result is that a single transducer failure leads to a reduction of the train speed even though the remaining transducer could still be able to control the pantograph position.

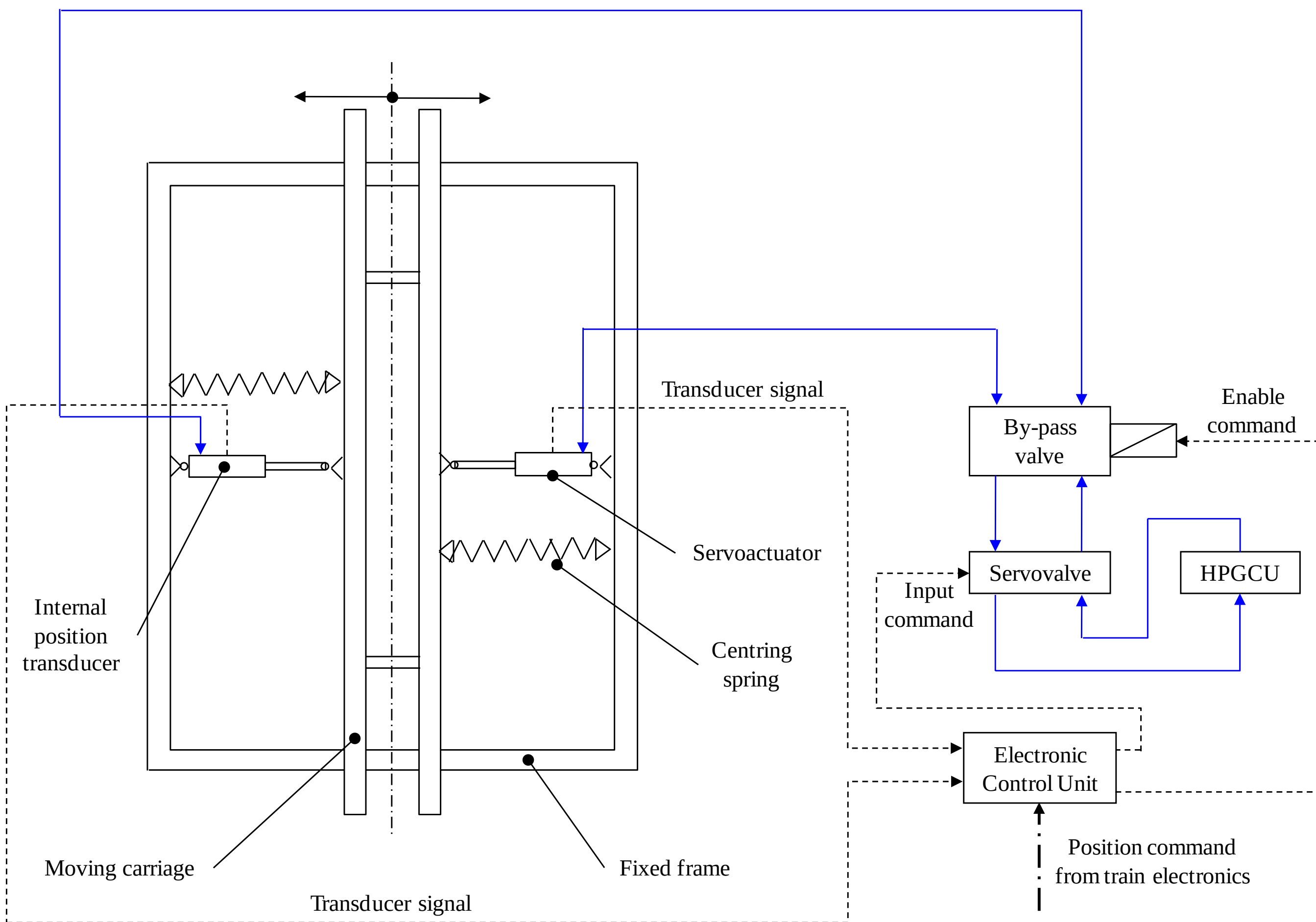

Figure 2. Concept schematics of the pantograph position control system

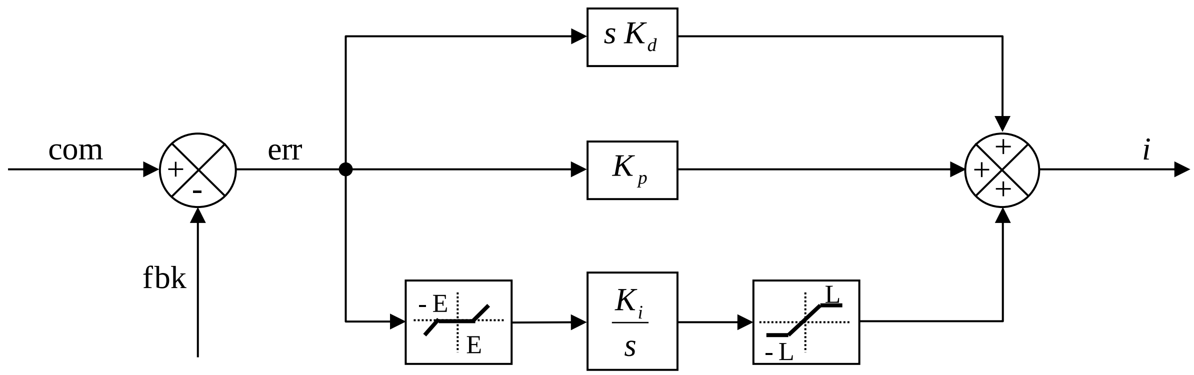

Figure 3. Block diagram of the pantograph control law

A research activity was then conducted to develop a more sophisticated diagnostic procedure allowing to detect the degradation of each individual transducer by appropriately processing all available signals by means of dedicated algorithms. This new diagnostic procedure brings about two benefits: it sorts out which of the two transducers is failed in case of discrepancy between the sensors signals and allows to detect a failure of the remaining active sensor after the other sensor has already failed. This allows the train to maintain the tilting system active, and thus a high train speed, after the loss of one of the two pantograph sensors, thereby improving the tilting system availability.

A further advantage brought about by the improved diagnostics is to simplify the maintenance operation. Presently, when a difference between the sensors output is signalled, the maintenance crew removes and replaces the entire pantograph, which is a time consuming and costly operation. The implementation of a health monitoring system able to specifically detect the failed transducer not only improves the tilting system availability but also reduces the maintenance costs.

3. Advanced health management system

The health management system herein presented was devised for being applied to legacy systems. It does not require any hardware modification, but makes better use of the available signals to enhance the ability of detecting an anomalous behaviour of the pantograph position control system allowing the tilting operation to continue also after a sensor failure.

The health management system is based on real-time modeling of the pantograph control system and consists of three separate functions:

- Coherence check
- Learning process
- Monitoring process

These three functions are continuously performed during the train ride, however, when a sensor failure is detected the learning process is permanently stopped. If a failure of the servovalve electrical section, or of its servoamplifier is detected, the learning process is temporarily stopped and it resumes after the train electronics has switched the servovalve control from the failed lane to the previously standby lane. The purpose of the learning process is in fact to continuously tune the values of the parameters used by the pantograph real-time model so it can be effective as long as all system components are operating correctly. If any component fails, the learning process loses its significance and the monitoring process continues using the last values of the system parameters that were determined by the learning process before the failure occurred.

The outputs generated by coherence check and monitoring process are then routed to a decision maker that fuses all information providing the train electronics with the indication of the health of the pantograph position control system. Figure 4 shows the flow chart of the processes performed by the health management system. The three functions performed by the health management system are described in the following sections.

4. Coherence check

The coherence check is performed on the signals of the two position sensors and on the servovalve current. The coherence check for the signals of the two position sensors consists of two operations:

- Verification that the output signal of the sensor is within a valid range
- Comparison between the output signals of the two redundant sensors

The signals A and B provided by the two position sensors are first checked to verify that they are in their valid range of 4 to 20 mA. In case the electrical output signal is outside this range a failure of that sensor is recognized, its signal is discarded and the pantograph control continues using the remaining sensor to close the position feedback loop. If both signals A and B pass the valid range check, they are compared to each other. If their difference is below an acceptable threshold, a signals coherence and hence a good health status is recognized; however, if a difference above the threshold prevails and lasts more than a given time, a lack of signals coherence is detected. In this case the position feedback, which is obtained by performing the average of the two sensors output signals, is obviously corrupted. When such condition occurs, the ensuing monitoring process will sort out which sensor is good and which failed thereby allowing the pantograph position control system to continue to operate. Based on an analysis of operational data the threshold for signaling a lack of coherence was set at a value corresponding to 6 % of the full actuators travel.

The servovalve coherence check is a monitor that is currently performed in the pantograph actuation systems for tilting trains. It is performed by implementing a current wrap-around which consists of measuring the actual current circulating through the servovalve coils and comparing it with the current command. Each of the two servovalve coils interfaces with one of the two sections of the control electronics, with the two coils operated in an active/standby mode. Only one of the two coils is active and the other coil is activated after a failure of the first coil is detected. When the coherence check detects a discrepancy of more than 15% of the rated current and such discrepancy lasts more than 100 ms, a failure of the electrical section of the servovalve is recognized. That section is then switched off and the previously standby section is activated. In case a second failure occurs, then the entire system is shut down and the train tilting is disabled.

It must also be noticed that the servovalve coherence check is instrumental in not only detecting the failures of the electrical section of the servovalve, but also those of its electrical driver.

5. Learning process

The learning process, as well as the monitoring process, makes use of a mathematical model of the pantograph position control system to perform their tasks. The basic concept for learning and monitoring processes is that for a servovalve controlled hydraulic actuator, servovalve current, flow rate and pressure differential across the servovalve control ports are three mutually related variables. For a given servovalve, if two of these variables are defined, the third one can be derived. Models of servovalve controlled electrohydraulic systems are shown in the literature (Borello, Dalla Vedova, Jacazio & Sorli, 2009 - Byington, Watson, Edwards & Stoelting, 2004). For the pantograph hydraulic actuation system the previously three referenced variables are either known or can be determined from the available information without additional sensors, as it will be discussed in the following.

The servovalve current i is a known variable at any instant in time since it is generated by the electronic controller and the fundamental issue is therefore to real time computing the values of flow rate and pressure differential from the signals provided by the actuators position sensors.

The calculation of the flow rate Q is relatively simple because the flow rate is the product of the actuators area A times their speed u. The actuators area is a known design parameter, while the speed can be determined by performing the time derivative of the actuators position provided by the position sensors. The pressure differential $(p_1 - p_2)$ can thus be determined form the well known servovalve pressure/flow relationship:

$$Q = k_v i \sqrt{(p_s - p_r) - (p_1 - p_2)} \tag{1}$$

where k_v is a known parameter defined by the servovalve characteristics, p_s and p_r are the supply and return pressure of the hydraulic system. These pressures are approximately constant values because the train hydraulic power generation is a constant pressure system and should the supply pressure decrease below normal, a hydraulic system failure is recognized by the relevant monitoring logic, while the return pressure is constant because the reservoir is open to the ambient.

It is important to notice that the control law of the pantograph position servoloop consists of a PI controller in which the control is essentially performed by the proportional gain, while the integrator gain has a small value, it has a saturation and its purpose is to cancel out the effects of the steady state errors that are originated by the servovalves offsets. By this way, the effects of the servovalve offsets are eliminated and the servovalve is centered in its hydraulic null when the servoloop error is zero. The current i of all equations of this paper is thus the current determined by the proportional gain, which actually determines the servovalve opening, while the contribution to the current given by the integrator gain exactly matches the servovalve offset.

Equation (1) describes the steady-state relationship between flow, pressures and servovalve current, and it does not include the servovalve dynamics. For the pantograph hydraulic control system the servovalve dynamics is about two orders of magnitude faster than that of the overall pantograph position servoloop; therefore, neglecting the servovalve dynamics for the real time modeling of the pantograph position control system does not introduce any appreciable error.

The pressure differential $(p_1 - p_2)$ across the actuators can however be determined from the balance of the forces acting on the actuators. This pressure differential is in fact equal to the force globally developed by the two actuators divided by their area.

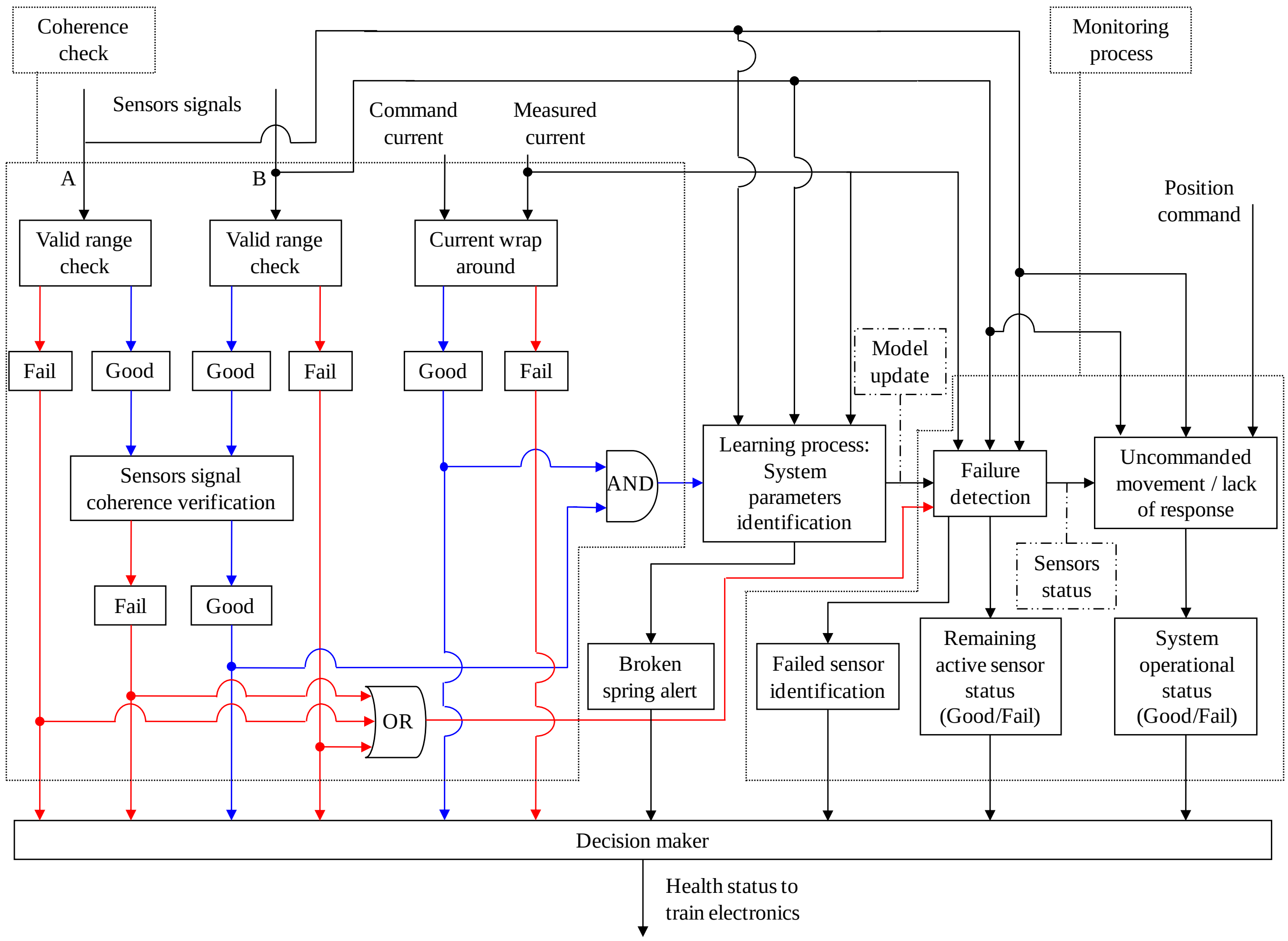

Figure 4. Flow chart for the health management of the pantograph position control system

The forces acting on the pantograph when it is moved away from its centered position are:

- Forces developed by the centering springs
- Friction forces
- Lateral component of the aerodynamic force acting on the pantograph
- Inertia force associated to the mass of the translating pantograph

For the pantograph position control system, the prevailing force acting on the actuators is by far the force developed by the recentering springs. The springs are preloaded and the force that they develop is a function of the actuators position as shown in Figure 5.

The spring forces are in theory a known quantity since the spring stiffness (k) is a design value. However, the construction tolerances of the mechanical structure accommodating the pantograph on the carbody roof and some variations of the dimensions associated to the temperature changes lead to some uncertainty on the value of the springs preload (F_0). While the spring rate can reasonably be considered a well defined parameter, the actual installed length of the springs and hence their preload can exhibit some variation that must be properly assessed.

The friction forces (F_f) are lower than the spring forces, but still give a significant contribution to the overall force acting on the actuators. The friction forces can exhibit a large variation, depending on the environmental conditions, on the condition of the carriage tracks along which the pantograph carriage moves, and on the progressive wear of the pantograph moving components with life.

The aerodynamic forces in the lateral direction and the inertia forces are little significant for this application and can be neglected by the health monitoring systems. They actually act as potential disturbances that were properly addressed in the assessment of the health management system robustness.

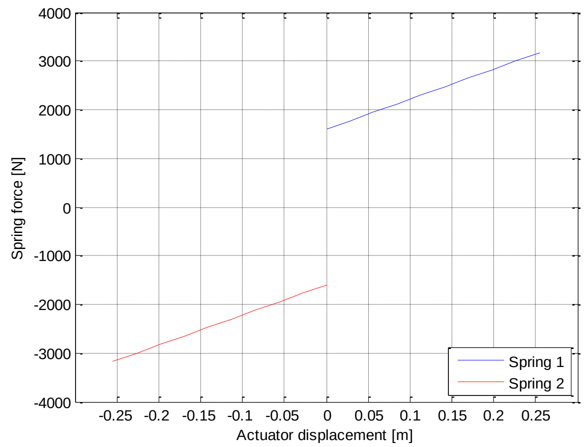

Figure 5. Diagram of actuators displacement versus spring forces

An important fact to be considered is that the force developed by the springs is always in the direction of centering the pantograph. The spring force thus acts as an opposing load when the pantograph carriage moves away from the centered position, while it acts as an aiding load when the pantograph carriage moves towards the centered position. On the contrary, the friction forces are always opposing the carriage movement.

Based on the above outlined considerations, after having defined a positive direction for the actuator travel x, the following simple equations for the balance of the forces acting on the actuators can be written (note that F_0 is a positive quantity because is the absolute value of the springs preload).

When $x > 0$:

$$(p_1 - p_2)A = F_o + kx + F_f \text{ for positive actuators speed } u \text{ (opposing load)} \tag{2}$$

$$(p_1 - p_2)A = F_o + kx - F_f \text{ for negative actuators speed } u \text{ (aiding load)} \tag{3}$$

When $x < 0$:

$$(p_2 - p_1)A = F_o - kx + F_f \text{ for negative actuators speed } u \text{ (opposing load)} \tag{4}$$

$$(p_2 - p_1)A = F_o - kx - F_f \text{ for positive actuators speed } u \text{ (aiding load)} \tag{5}$$

When the train negotiates a curve the pantograph is commanded to move laterally in one direction to counteract the carbody tilting in the other direction, that is followed by a command back to zero when the train exits the curve. Over this period of time the learning process is activated.

While the pantograph is moving away from center, the opposing load condition Eq. (2) or Eq. (4) prevails, while the aiding load condition Eq. (3) or Eq. (5) prevails when the pantograph travels back to center. Therefore, the learning algorithm works in the following way.

When the train enters a curve and the pantograph travels away from center, the algorithm uses Eq. (1) to compute the value of $(p_1 - p_2)$, which is then used by Eq. (2) or Eq. (4) to compute the value of $(F_0 - F_f)$ based on the value of the actuator position x and on the known design parameters A and k. This calculation is performed for predetermined values of the actuators position x. When the train exits the curve and the pantograph moves back to the centered position, the same calculations are performed for the same values of actuators position x, but using Eq. (3) or Eq. (5), thereby determining the values of $(F_0 - F_f)$. Since no changes of springs preload and frictional losses occur in the short time interval between entering and leaving a curve, by knowing $(F_0 + F_f)$ and $(F_0 - F_f)$ for the same value of x it is possible to find out the values of F_0 and F_f.

The computed values of F_0 and F_f are stored in memory for each value of actuator travel x and a moving average is then performed which adapts the values of F_0 and F_f to the variations that can occur in service. However if a sudden large reduction of spring preload F_0 is detected by the learning process, this would be the result of a broken spring; an alert is then generated and sent to the decision maker.

The above described learning process occurs only when the absolute value of the actuation speed u is above a minimum threshold u_T, since very small actuation rates could lead to less accurate results. The learning process concept block diagram is shown in Figure 6.

The learning process continues as long as the coherence checks provide a positive output. If a sensor failure is recognized or if a difference between the signals of the two position sensors above the established threshold δx_T is detected, and that difference lasts more than a given time δt_0, then the learning process is discontinued and the modeling process reverts to the monitoring process described in the next section.

6. Monitoring process

The logic for the monitoring mode is described by the block diagram of Figure 7. The monitoring process performs two basic functions:

- Detects uncommanded movements or lack of response of the pantograph actuators (Figure 7 – a)
- Detects sensors failures that were not identified by the coherence check (Figure 7 – b)

Detection of uncommanded movements or lack of response is a relatively straightforward operation: the actuators rate computed from the time derivative of the position signals is compared with the rate of change of the position command. If a discrepancy exists and lasts more than a given amount of time, a failure is recognized. This monitor is continuously performed, but in case one of the two position sensors is

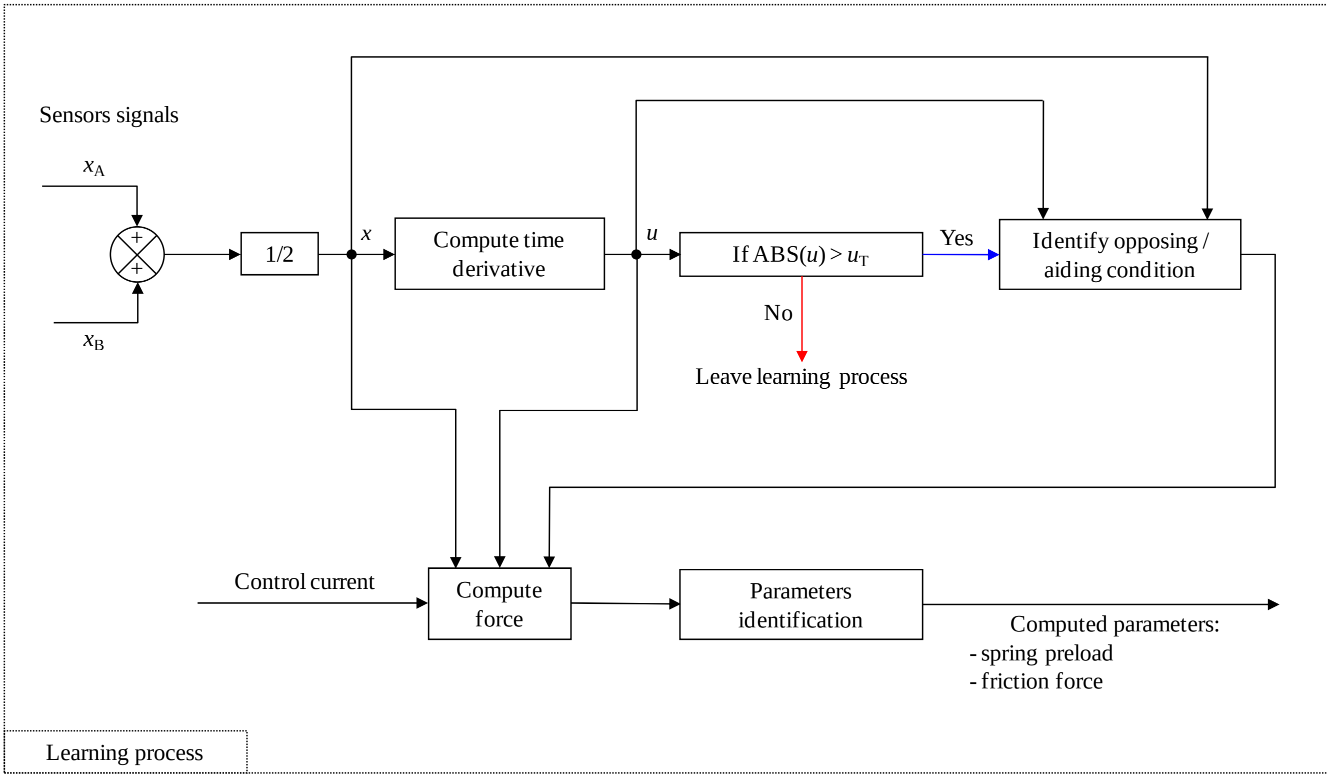

Figure 6. Concept block diagram of the learning process

failed, the uncommanded movement / lack of response monitor is temporarily stopped and it is resumed after the other monitors have identified which of the two position sensors is the good one. This temporary pause of about 100 ms for the uncommanded movement / lack of response monitor is instrumental in avoiding a false indication of wrong system operation. Detection of sensors failure not identified by the coherence check is a more challenging task, which is described hereunder.

The actuator speed is computed by performing the time derivative of the signals x_A and x_B received from the two position sensors; two values u_{TA} and u_{TB} are then obtained for the actuator speed. These values are compared with the actuator speed u_{MA} and u_{MB} computed from the system model described in the previous section by using the last values of F_0 and F_f determined in the course of the learning process. The absolute value $|\delta u|$ of the difference between actual and computed actuator speed is processed by a filtering element whose purpose is to eliminate undesired noise in the monitoring process. The filtering element sets its output e equal to $|\delta u|$ only when $|\delta u|$ is greater than a minimum value u_{MIN}. This prevents differences resulting from the inaccuracies of the modeling process to be counted as errors. The resulting errors e_A and e_B for the two position sensors are divided by the actuator speed u_{MA} and u_{MB} in order to obtain two non-dimensional quantities, e_A' and e_B'. These non-dimensional errors are then integrated with time and the integrators outputs I_A and I_B are used for recognizing a sensor failure. If the coherence check signalled a difference between the two sensors but was unable to decide which of the two was the failed one a cross monitoring logic of the monitoring process is able to sort out the failed sensor. If a sensor is malfunctioning, its relevant integrator output (I_A or I_B) grows faster than the other, and by looking at which of the two outputs (I_A or I_B) is greater, it is possible to sort out which is the failed sensor.

It must be emphasized that for this condition the monitor does not compare the computed value of a certain quantity against an acceptable limit and has to decide whether a failure has occurred or not. The monitor already knows from the coherence check that a failure exists and simply compares two quantities (I_A and I_B) to realize which of the two sensors is failed. In this condition, there is an extremely low probability of error: the quantity I relevant to the failed sensor will definitely be greater than that for the healthy one and the failed sensor can be positively identified with practically zero error probability.

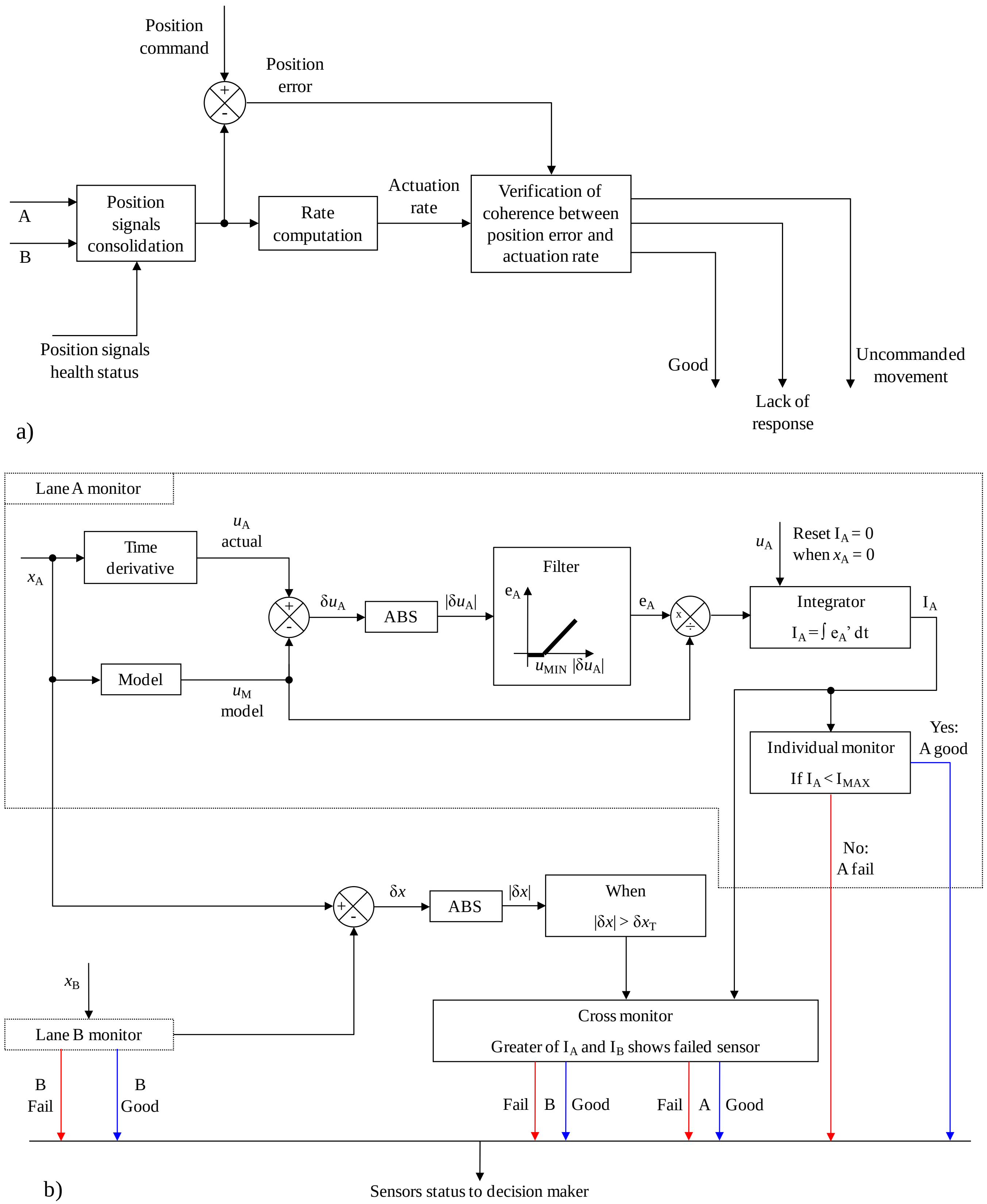

Figure 7. Concept block diagrams of the monitoring process

When only one sensor is active because the other one was recognized failed, the monitoring process continues for the remaining healthy one using the last values of F_0 and F_f determined in the course of the learning process. Obviously, in this case it is not possible to compare the signals of the two sensors. Therefore, the monitoring logic relies on comparing the time integral of the absolute value of the error e resulting from the filtered difference between the actual u_A and computed u_M actuators speed with a limit threshold I_{MAX} . When the integrator output I becomes greater than I_{MAX} a failure is recognized.

Since the monitoring process is meaningful only when the pantograph is commanded to move, the integrators outputs (I_A and I_B) are reset to zero when the pantograph is centered. This instruction prevents that occasional disturbances, not related to sensors malfunctionings, are progressively added by the integrator and possibly generate a false alarm.

Since the monitoring process implemented when only a single sensor is less accurate than the one for the case of two sensors active, the limit I_{MAX} beyond which a sensor failure is recognized cannot be set too low to minimize the risk of false alarms. A comprehensive simulation campaign was thus performed to establish an optimum value of I_{MAX}, such to obtain the fastest possible recognition of a failure while minimizing the risk of false alarms.

7. Decision maker

The decision maker consists of a logic routine accepting the output signals from the coherence check and the monitoring process to provide the train electronics with the information of the health status of the pantograph control system.

The decision maker issues the warning of a position sensor failure (A or B) if such failure has been detected either by the coherence check or by the monitoring process. In case a failure of the remaining active sensor is detected after the other sensor had already failed, an alarm is issued signaling the loss of pantograph position information.

If the current wrap around performed by the coherence check detects a failure of the servovalve electrical section, a warning is issued such that the train electronics can activate the other servovalve electrical channel.

If a subsequent failure of this other section of the servovalve occurs, then an alarm is issued indicating loss of pantograph control.

If an uncommanded movement, or a lack of response is detected by the monitoring process, the decision maker issues again an alarm indicating loss of pantograph control.

8. Performance assessment of the health management system

The merits of the health management system presented in this paper were assessed running several simulations of a model representing the dynamic response of a train pantograph. In particular, the mathematical model specifically referred to the Alstom Ferroviaria "Nuovo Pendolino" train.

In order to assess the merits of the diagnostic system, a comprehensive complex mathematical model representing both tilting and pantograph actuation systems was developed. This model is of a physical based type, based on the mathematical relationships among the state variables and the physical parameters. The model proved to be very accurate when later compared with the data measured during revenue service operations. Several time histories of tilt angle commands and actual responses were available, and the same sequences of commands were injected into the model and the relevant responses were computed. An example of comparison is shown in Figure 8, and similar accuracies were found for all type of tilt commands, and the validity of the system model was thus positively verified.

This mathematical model acts as a virtual hardware was then used in place of the actual hardware to verify the performance of the diagnostic system. Several simulations were performed, both in normal and in failed conditions, in order to assess the ability of the health management system to properly identify a failure of one or both position transducers and to avoid false alarms. Failures of the servovalve and of the actuators leading to uncommanded movements or lack of response were also simulated, but do not represent a specific advance since the relevant monitoring logics are normally implemented in hydraulic servocontrols. The following of this paper is thus focused to the failure cases of the position sensors. Several simulations were also performed changing the system physical parameters in order to check the ability of the learning process to properly adapt the model parameters to the varying conditions so as to avoid false failure indications.

Simulations were initially run with the nominal values of the system parameters to test the health management system under normal operating conditions. Several pantograph movements were commanded so as to simulate different rides, changing both the amplitude and the velocity of the pantograph movements.

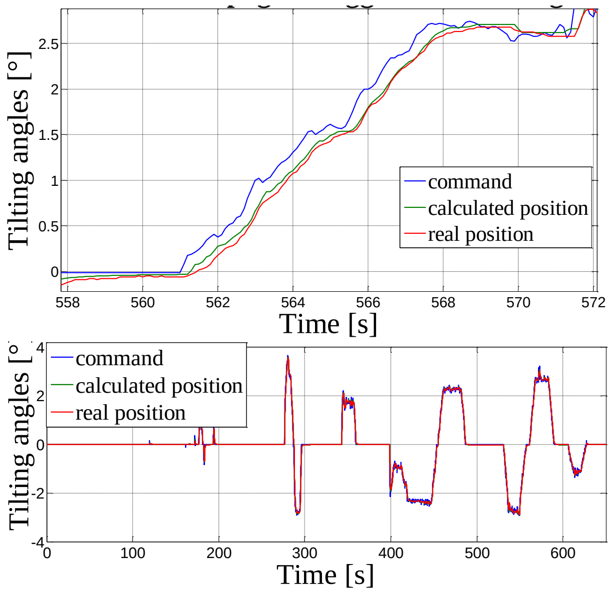

Figure 8. Example of comparison between virtual hardware model results and test data

An example of the simulations for operation with nominal values of the pantograph control system parameters is shown in Figure 9. Since the commands to the pantograph actuators are synchronized with the commands to the tilting actuators, the position commands reported in the y axis of the upper diagram of Figure 9 are indicated as tilt angle commands that are comprised from 0° to 8° (maximum tilt angle). The steady conditions, which are representative of a travel either in the middle of a curve or in a straight track, last 5 s. The simulation of Figure 9 was conducted assuming that both position transducers are initially operating correctly and that transducer 1 fails at time t = 40 s. In this case the integral of the error for the remaining active sensor was computed as defined in section 5 of this paper.

Looking at Figure 9 it can be seen how the error integral always remains below the fault indication limit and no false alarm indication is then generated by the monitoring process.

Simulations were then run changing the values of the parameters of the pantograph control system, that were varied in a range can be reasonably expected for the trains in regular revenue service. The purpose of these simulations was to test the ability of the learning process to progressively tune the model values tuning part such to avoid false failure indications. The physical parameters that were made vary in order to simulate the whole range of operating and environmental conditions were:

- External load
- Spring rate
- Spring preload
- Friction force
- Supply pressure

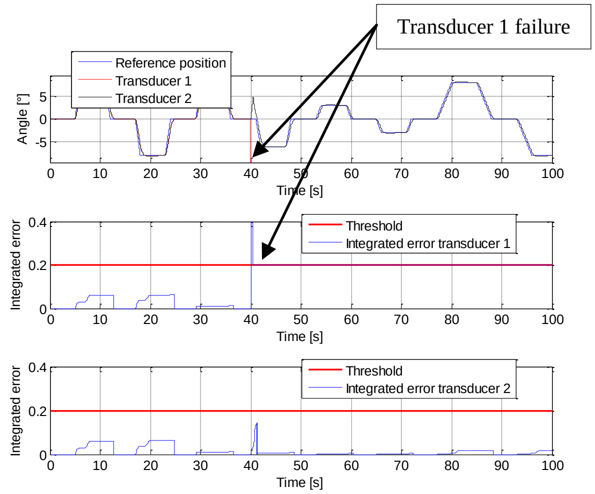

Figure 9. Health management system assessment: one sensor active - nominal values of the system parameters

Examples of the health management system performance are reported in Figure 10 and Figure 11. In particular, Figure 10 refers to the case in which the pantograph is subjected to a cross wind load of 3000 N, while Figure 11 corresponds to an operation with a supply pressure reduced from 31.5 to 25 MPa. As for the previous simulation case shown in Figure 9, it was assumed that a sensor failure occurred at time 40 s in order to check the ability of the monitoring process to correctly detect the failure. For the case in Figure 10 it can be seen that as the cross wind load is applied at time zero, as long as the sensors are operating correctly the error integral remains well below the warning threshold, and the value that is built up at the end of each curve progressively decreases because the learning process adapts the values of the system parameters to the changed conditions. No false alarm is generated and the ability is shown of the learning process to properly adapt the values of the model parameters.

For the case in Figure 11, the sudden drop of the supply pressure from 31 to 25.5 MPa causes the integral of the error to exceed the threshold for a very small amount of time for both sensors. Since the two position sensors are actually operating correctly and passed the coherence check, the simultaneous overcoming of the threshold for the two error integrals does not trigger a failure indication. When a transducer 1failure is actually injected at time t = 40 s, a loss of coherence between the two sensors is recognized and the error integral grows much above the threshold, thus indicating the sensor failure. From that time on the sensor signal is discarded and the operation continues counting only on the signal of the other transducer.

After having verified that no undue false alarms were generated by the health management system for any combination of environmental and operating conditions of the pantograph control system, simulations were then run injecting different types of failures, and again this was done over a wide range of service conditions for the train.

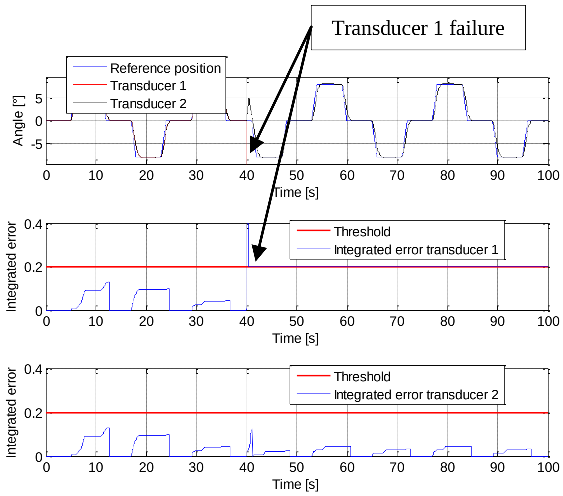

Figure 10. Health management system assessment: one sensor active - presence of a cross wind load of 3000 N

Failures such as an internal short or a broken wire of one of the position sensor are immediately picked up by the coherence check, thus the simulations were focused to those types of failures that are not easily detected by the monitoring logic presently implemented in the trains in service.

Sensors failures addressed by the simulations were:

- Step change of the sensor offset
- Step change of the sensor gain
- Slow change with time of the sensor offset
- Slow change with time of the sensor gain

A few typical examples of the simulations results are shown in Figure 12 through Figure 15. Figure 12 shows the case in which the sensor 1 offset is subjected to a step change of 6 %, which could be the result of an electrical degradation, or of a permanent mechanical realignment determined by an occasional large jerk during the train ride. After the offset change the output signals of the two sensors are different and the coherence check will thus alert of a failure. The ensuing monitoring process then looks at the error integrals and easily identifies the failed sensor because its error integral is much greater than that of the healthy sensor. The same happens for the case of a step change of the gain of one of the two sensors (Figure 13). When the pantograph is commanded to move away from center a difference between the output signals of the two sensors greater than the threshold is detected by the coherence check, which thus issues a failure alert. The ensuing comparison between the error integrals performed by the monitoring process identifies the failed sensor because its error integral is much larger than that of the good sensor. Results similar to those shown in Figure 12 and Figure 13 are obtained for the cases of a progressive variation of a sensor offset or of a sensor gain. When the difference between the output signals of the two sensors is large enough to activate the lack of coherence alert, the difference between the error integrals computed by the monitoring process is large and the identification of which of the two sensors is the failed one can be performed without error.

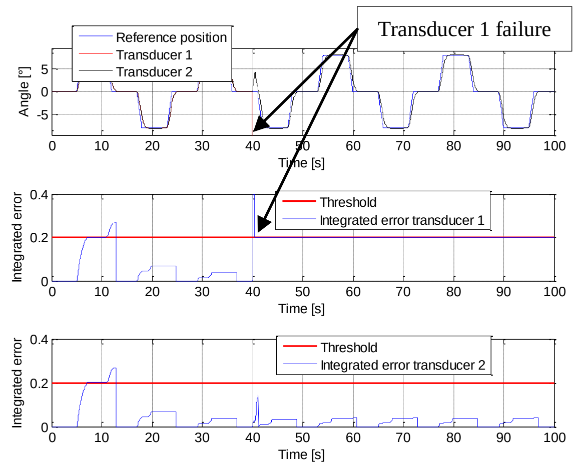

Figure 11. Health management system assessment: one sensor active - system supply pressure reduced from 31.5 MPa to 25 MPa

Progressive variations of one sensor offset and gain were simulated and are shown in the diagrams of Figure 14 and Figure 15 to assess which was the maximum error attained in the pantograph position measurement before the monitoring process recognizes the sensor failure. The simulations were performed using a heavy duty track as pantograph position command sequence. It can be seen from the simulations results that in both cases the error integrals tend to increase until they reach a point for which a pantograph position command greater than a minimum value makes the error integral to overcome the threshold, thereby triggering the failure alert. In particular, it can be observed from Figure 14 how the error integral overcomes the threshold a few times between approximately 350 s and 550 s before the failure indication is eventually activated. This is due to the fact that, because of the progressive offset variation, the transducer indicates an incorrect pantograph position, but the pantograph position error is not large enough to activate the lack of coherence check. The transducer is eventually declared failed at time 550 s, when the position error of the degrading transducer leads to a difference from the healthy transducer signal such to signal a lack of coherence. As this alert is generated, the ensuing monitor is enabled which recognizes as failed the transducer with higher error integral. The signal of the failed position sensor is ignored from then on and no more signals taken into account in the pantograph position servoloop. For the cases of Figure 14 and Figure 15 the failure indication occurs when the maximum error of the position transducer is respectively 6 % and 9 %.

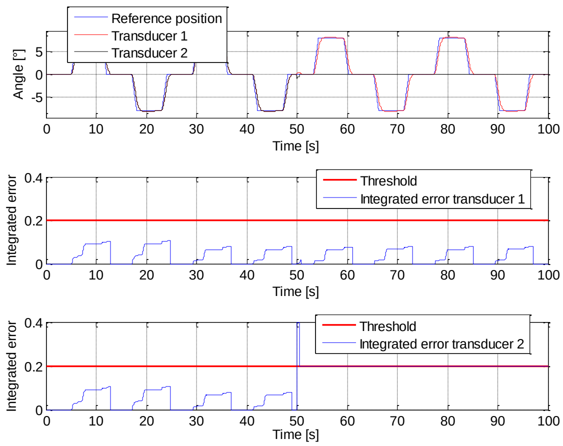

Figure 12. Failure simulation scenario #a: The two position sensors are initially good, then position sensor #2 is subjected to a step change of its offset

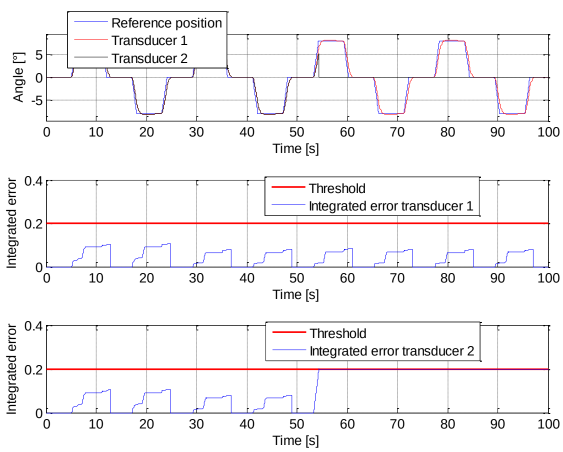

Figure 13. Failure simulation scenario #b: The two position sensors are initially good, then position sensor #2 is subjected to a step change of its gain

9. Conclusion

The work herein presented was carried out in order to define a technique able to recognize the failure of the sensors used to measure the lateral position of the pantograph of high speed tilting trains equipped with laterally translating pantographs with minimum risk of missed failures and false alarms. This would allow an unabated operation of the train tilting system after a failure of one of the two lateral position sensors of the pantograph, while the present monitoring system disables the tilting operation and reduces the train speed after a single sensor failure.

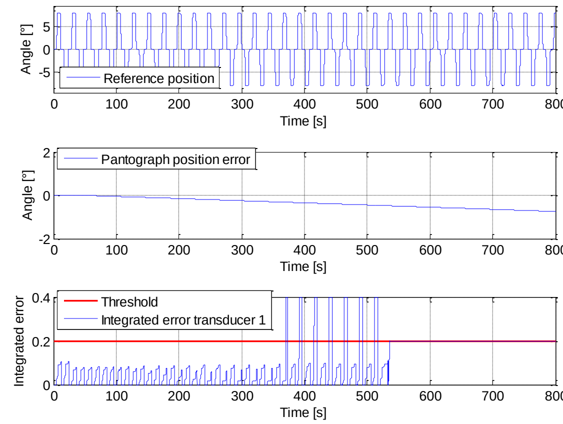

Figure 14. Failure simulation scenario #c: The two position sensors are initially good; then sensor #1 undergoes a progressive variation of its offset

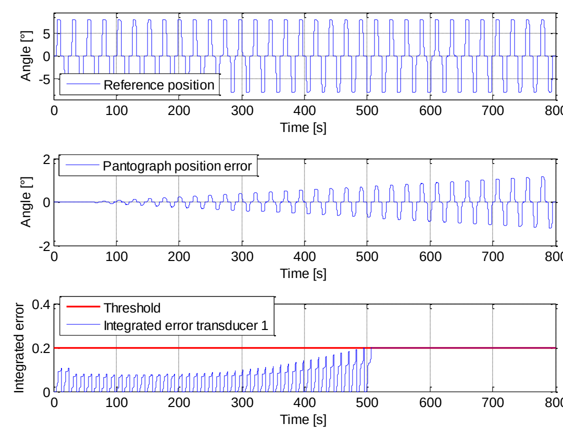

Figure 15. Failure simulation scenario #d: The two position sensors are initially good; then sensor #1 undergoes a progressive variation of its gain

The health management system described in this paper was first tested simulating train rides over different tracks and for the entire range of operating and environmental conditions, and appropriate limits for the failure detection were established to prevent false alarms. Then, all types of sensors failures and malfunctionings were injected and the ability of the health management system to recognize them was positively assessed.

The results of the entire simulation campaign proved the robustness of the proposed health management system and a confidence was hence gained in its ability to detect a sensor failure or malfunctioning with minimum risk of false alarms or missed failures. The implementation of such health management system on a tilting train will thus enable the tilting operation to continue after a failure of a pantograph lateral position sensor, hence allowing the train to maintain its high speed travel for the remainder of the ride. Furthermore, the positive recognition of a sensor failure would greatly ease the maintenance operation, since the failed sensor can be replaced without the need of removing the entire pantograph assembly from the train roof.

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NOMENCLATURE

i	servovalve current
Q	servovalve flow rate
k_v	servovalve deflux coefficient
A	actuators area
x	actuators displacement
u	actuators speed
p_1	pressure at servovalve control port 1
p_2	pressure at servovalve control port 2
p_s	hydraulic system supply pressure
p_r	hydraulic system return pressure
k	springs stiffness
F_0	springs preload
F_f	friction forces
δt_0	learning process time threshold
e	filtered actuator speed error
I	integral of the actuator speed error

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