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(54) SYSTEM FOR MONITORING AND PREDICTIVE MAINTENING THE STATE OF WEAR OF MECHANICAL COMPONENTS AND OPERATION METHOD THEREOF

(57) The present invention relates to a system (S) for monitoring and predictive maintenance of the state of wear of mechanical components of a railroad car (R), responsible for driving dynamics, of the type comprising a chassis (C), two wheel-axles (A), a bogie frame (T) and dampening (D1, D2), comprising: a logic control unit (U) comprising a signal processing program, at least one plurality of sensors (1), which can be placed on said chassis (C), wheel-axles (A), bogie frame (T) and dampening (D1, D2), capable of detecting operation data of said railroad car (R) and sending corresponding signals to said logic control unit (U), said system (S) being characterized in that said signal processing program is capable of processing said signals so as to extract real characteristic data of said mechanical components of said railroad car (R), comparing said real characteristic data with nominal theoretical values in real time, emitting an alarm signal if the result of said comparison is outside a predetermined range of values.

The present invention also relates to an operating method of said system (S).

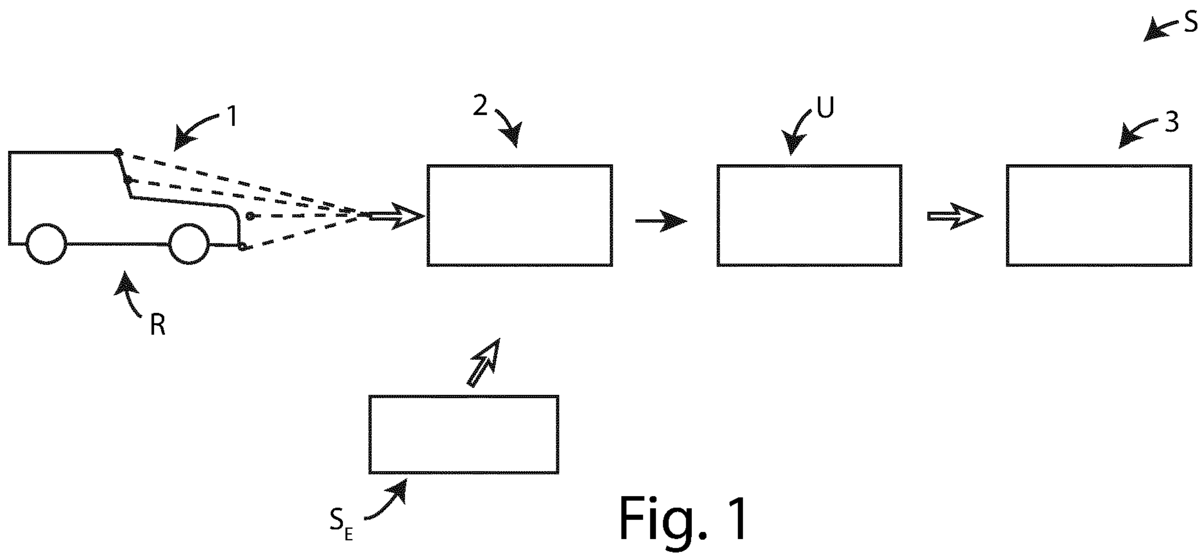

Fig. 1

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Description

[0001] The present invention relates to a system for monitoring and predictive maintaining the state of wear of mechanical components, in particular of rolling railway vehicles.

[0002] More in detail, the invention relates to a system of the aforementioned type, designed and realized in particular to monitor the state of wear, and perform predictive maintenance of the mechanical components that determine the vehicle dynamics of a rolling stock, in particular of a railway vehicle, but which can be used for any vehicle including mechanical components, for which wear status assessment is required.

[0003] In the following the description will be addressed to the monitoring of the state of wear of mechanical components of railway vehicles, but it is clear that the same should not be considered limited to this specific use.

[0004] As is well known, various methodologies are currently used for vehicle maintenance.

[0005] A known model, known as *model based,* is based on the schematization of the real model in a mathematical model using differential equations in such a way that the real and the simulated system respond in the same way to external stresses.

[0006] This method allows the evaluation of the physical system through the comparison between the two models and the analysis of the deviation between the results obtained and those expected, obtained from the simulation.

[0007] A disadvantage of the *model based* is due to the fact that it is necessary to write the differential equations that best approximate the system, as a complex system can have many variables that make the system highly non-linear.

[0008] A further model, known as *rules based,* is based on rules or conditions, through which the operation of the system is described, and requires a deep knowledge of the system and its design features.

[0009] This method, although conceptually simple, becomes non-trivial in practice as it provides a very stable system and in the case of many variables and conditions the rules become too many and not easy to manage.

[0010] A further model, known as *case based,* is based on the analysis of the system conditions with respect to which the operating status is identified, assumes a large number of data accumulated over time, and relating to the various operating conditions that are processed and taken as a reference.

[0011] The system is useful in the case in which the mapped cases are many and cover all, or a good part of the operating range of the system, the latter must be stable so as to be able to work with the interpolations between the cases in the database, in other conditions than those prescribed, one must be cautious in applying the model.

[0012] Yet another model, known as *pattern recognition,* is based on the deterioration trends consolidated over time, represented by graphs, which reproduce the deterioration status of the monitored characteristics and a point is set, beyond which action must be taken by replacing the component before that the curve reaches the end of the component's useful life.

[0013] In order to apply this method, it is necessary to have tested and validated the deterioration curves through experiments and precise measurements on the generic system as the maintenance times are fixed based on the calculation of the curve.

[0014] It is evident that each of these known models and systems have disadvantages, as described above.

[0015] In light of the above, it is, therefore, object of the present invention to provide a system for monitoring the dynamics of the railway vehicle, to which it is applied, for detecting the wear state of mechanical components, and which is able to apply even at the same time at least all four the previous models, evaluating even a few essential elements, in order to be reliable.

[0016] A further object of the present invention is to provide the tools necessary for carrying out the method and the apparatuses that carry out this method.

[0017] It is, therefore, the specific object of the present invention a system for monitoring and predictive maintenance of the state of wear of mechanical components of a railroad car, responsible for driving dynamics, of the type comprising a chassis, two wheel-axles, a bogie frame and dampening, comprising a logic control unit comprising a signal processing program, at least one plurality of sensors, which can be placed on said chassis, wheel-axles, bogie frame and dampening, capable of detecting operation data of said railroad car and sending corresponding signals to said logic control unit, said signal processing program is capable of processing said signals so as to extract real characteristic data of said mechanical components of said railroad car, comparing said real characteristic data with nominal theoretical values in real time, emitting an alarm signal if the result of said comparison is outside a predetermined range of values.

[0018] Further according to the invention, said signal processing program comprises a system of differential equations capable of calculating an expected model of operation of said mechanical components, starting from said nominal values, calculating a real model of operation of said mechanical components, starting from said real characteristic data, comparing said real model with said expected model, calculating the deviation between the real model and the expected model, comparing the deviation with a predetermined range of values.

[0019] Preferably according to the invention, said plurality of sensors comprises accelerometers, inclinometers, gyroscopes and encoders.

[0020] Still according to the invention, said operation data detected are vibrations, triaxial accelerometry, triaxial gyroscopy, triaxial inclinometry, speed and distance traveled by said railroad car.

[0021] Always according to the invention, said system comprise an acquisition data device capable of receiving said signals detected by said plurality of sensors and digitizing and converting said signals.

[0022] Further according to the invention, said system may comprise a predictive maintenance management device of said railroad car, capable of receiving said alarm signal and activating maintenance operations.

[0023] Preferably according to the invention, said system may comprise an energy recovery system capable of taking vibrational, and/or acoustic, and/or electromagnetic, and/or solar, and/or photovoltaic, and/or wind and/or micro-wind energy and converting it into electrical energy.

[0024] It is further object of the present invention an operation method of a system for monitoring and predictive maintenance of the state of wear of mechanical components of a railroad car, of the type comprising a chassis, two wheel-axles, a bogie frame and dampening, comprising the following steps:

a. detecting operation data of said railroad car and sending corresponding signals to said logic control unit;
b. carrying out a pre-processing on said signals, such as digitization and conversion;
c. processing said signals to extract real characteristic data of said mechanical components of said railroad car;
d. comparing said real characteristic data with nominal values of said mechanical components, in real time;
e. checking if the result of said comparison falls within a predetermined range of values;
f. emitting an alarm signal if the result of said comparison is outside said predetermined range of values;
g. storing said pre-processed signals and said compared data in said step *d.*

[0025] 9. Method according to the preceding claim, characterized in that said it comprises the following step:
h. estimating the time interval in which the monitored mechanical component can pass through an anomaly condition, in order to manage the predictive maintenance activities related to it.

[0026] Further according to the invention said method may comprise the following step:
h. estimating the time interval in which the monitored mechanical component can pass through an anomaly condition, in order to manage the predictive maintenance activities related to it.

[0027] The present invention will be now described, for illustrative but not limitative purposes, according to its preferred embodiments, with particular reference to the figures of the enclosed drawings, wherein:

figure 1 shows a block diagram of the monitoring and predictive maintenance system of the wear state of the mechanical components, object of the present invention;
figure 2 shows a schematic view of the installation of the system object of the present invention, on a vehicle;
figure 3 shows a schematic view of the vehicle;
figure 4 shows a top view of the components of the vehicle of figure 3, on which the system is installed;
figure 5 shows a schematic view of a portion of the vehicle of figure 3;
figure 6 shows a block diagram of the method of operation of the system object of the present invention;
figure 7 shows a schematic top view of the components shown in figure 4;
figure 8 shows a schematic view of a part of the components shown in figure 7; and
figure 9 shows a flow diagram of the method of operation of the system object of the present invention.

[0028] In the various figures, similar parts will be indicated by the same reference numbers.

[0029] With reference to figures 2, 3, 4, 5, and 7, the structure of a railroad car R, on which said system is installed, is first described.

[0030] A railroad car R generally consists of seven masses, a chassis, two bogie frames and four wheel-axles or axles.

[0031] The chassis C is the outer casing of the railroad car R, which contains things and/or people.

[0032] Each mass is coupled to the others by means of dampenings with suitable damping and/or stiffness.

[0033] The wheel-wheel-axles A are connected to the bogie frame T via the primary dampening D1, while the bogie frame T is connected to the chassis C via the secondary dampening D2.

[0034] The bogie frame T is the backbone of the railroad car R and consists of two longitudinal members connected by crossbars.

[0035] The wheel-axles A rest with the wheels on the railway line.

[0036] With reference to figure 1, the system S for monitoring and predictive maintenance of the wear state of the mechanical components, object of the present invention, essentially comprises a plurality of sensors 1, a data acquisition device 2, a logic control unit U, and a maintenance management device 3.

[0037] The system S is powered by a further energy recovery system S_E, as will be described in detail below.

[0038] The system S is able to monitor the state of wear of the components that influence the vehicle dynamics of a railroad car R and to predict the need to replace a component.

[0039] By analyzing motion and how it is influenced by the state of a component, the system S recognizes which component and to what extent is wearing, in order to promptly intervene in the replacement or maintenance of the latter or not intervene at all if, despite the end of the component's theoretical useful life, it is still in good condition.

[0040] Said plurality of sensors 1 is installed on said railroad car R.

[0041] In particular, four sensors are installed on the four bushings, then a first sensor 11 on a first bushing, a second sensor 12 on a second bushing, a third sensor 13 on a third bushing and a fourth sensor 14 on a fourth bushing.

[0042] Two other sensors are installed on the center line of the wheel-axles A, in particular a fifth sensor 15 on a wheel-axle A, and a sixth sensor 16 on another wheel-axle A.

[0043] A seventh sensor 17 is installed on the chassis C.

[0044] Said plurality of sensors 1 comprises accelerometers, inclinometers, gyroscopes and an encoder, and is capable of detecting signals such as vibrations, triaxial accelerometry, triaxial gyroscopy, triaxial inclinometry, speed and distance traveled.

[0045] In particular, there are detected: acceleration, speed, displacements along the X, Y, Z axes, measured in the center of gravity of the wheel-axles A, of the bogie frame T and of the chassis C.

[0046] In particular, the first X-axis is the running direction of the railroad car R along the tracks, with a direction concordant with the advancement, the second Y-axis is perpendicular to the tracks, therefore to said first X-axis, the third Z-axis is orthogonal to the plane passing through said first X and second Y axis, so as to form a left-handed triad.

[0047] Speed and displacements are calculated by integrating acceleration and filtering to eliminate errors.

[0048] The gyroscopy in rad/s is also measured around the rotation axes around the center of gravity of the wheelset, the bogie frame T and the body and the speed of the railroad car R in m/s.

[0049] Signals are pulses or voltage changes.

[0050] Said data acquisition device 2 is a microcontroller or an acquisition card, which is able to receive the signals detected by said plurality of sensors 1 and to digitize and convert said signals.

[0051] Said control logic unit U is able to receive said digitized and converted signals from said data acquisition device 2.

[0052] Said control logic unit U is able to process said signals by means of a reference model based on the differential equations that define the model physical and relative dynamic behavior, as will be described in detail below.

[0053] Said maintenance management device 3 essentially comprises a remote maintenance server and/or a *cloud* maintenance, for remote consultation, a maintenance program or application that can be used in remote devices such as *smartphones,* and an operator interface for the assisted execution of the maintenance intervention.

[0054] Said system S is also powered by a further energy recovery system S_E of an energetic, and/or vibrational, and/or acoustic, and/or electromagnetic, and/or solar, and/or photovoltaic, and/or wind, and/or or micro-wind, as described below.

[0055] As regards thermal energy, the energy produced or dispersed in the form of heat by the engine and/or by the heating elements or by the generation of heat from friction and/or thermal dispersion, is transformed into electrical energy and stored to power the electronics of the system S.

[0056] As regards the vibrational or dynamic energy, the mechanical energy that can be used during the movement of the railroad car R can be used to be transformed into electrical energy which, once accumulated, can be used for power supply the electronic devices of the system S.

[0057] As for the acoustic or electromagnetic energy, the energy related to the acoustic and electromagnetic pollution present on board the train can be suitably converted into electrical energy which, once accumulated, can be used for power supply of the electronic devices of said system S.

[0058] As regards solar energy, solar-photovoltaic, wind, micro-wind, from all these sources it is possible to recover both when the train is stopped, by means of solar sources, and when the train is in motion, by means of wind sources, the energy which, suitably transformed into electrical energy, can be appropriately accumulated and used to power the electronics of the system S.

[0059] The energy is accumulated through the use of a battery, or in some cases by at least one supercapacitor, it is then distributed to all electronic devices of the system S.

[0060] This allows a continuity to the measurements also in the moments in which the main energy system, called *energy harvesting,* is unable to power system S directly.

[0061] The operation of the monitoring and predictive maintenance system S of the wear status of mechanical components described above is as follows.

[0062] In a first step, said plurality of sensors 1 acquires the signals described above.

[0063] In a second step, said signals are pre-processed by said data acquisition device 2.

[0064] In this step any errors due to the imperfect installation of the sensors 1 or to installation limits, are eliminated, such as for example considering the eccentricity from the center of gravity, or applying the transport theorem to transfer a force calculated to a point other than the optimal one because the installation of sensor 1 was impossible, due to lack of space or because it was physically impossible, for example if the center of gravity is inside the wheelset, and finally, elimination of noise and disturbances, through digital filters or correction coefficients.

[0065] The data are: acceleration, speed and displacements along said first X, second Y and third Z axis, measured in the center of gravity of the wheel-axles A, of the bogie frame T and of the chassis C, gyroscopy in rad/s around the rotation axes around the center of gravity wheelset, bogie frame T, and chassis C, vehicle speed in m/s.

[0066] Speed and displacements are not directly measured parameters, but are calculated from the integration of the acceleration and filtered to compensate for possible errors.

[0067] The data are stored for a certain instant of time or space so the integration carried out to obtain the displacements can take place in two different ways, based on the form of the adopted acquisition, for example acquisition based on time or acquisition based on the distance traveled from the railroad car R.

[0068] For the acquisition based on time, the data are collected at constant intervals, for example every 8 milliseconds, while based on the distance traveled the time is not constant, and the movements are obtained by integrating each time with respect to the value of the time resulting from the displacement, for example every cm the instant of time is acquired, which therefore can vary according to the speed at which it moves so that the integration takes place with a value indirectly obtained.

[0069] This temporal acquisition step is also spatially scanned by means of the encoder and a clock, in case an absolute time is desired or the time can be acquired by the system S in a relative manner, resetting the timer at start-up.

[0070] The displacement data is of two types.

[0071] The displacements entered in the input data are the relative micro-displacements calculated between one time instant and another of the parts of the railroad car R, which must be distinguished from the movement data of the whole railroad car R.

[0072] In a third step, the data so processed are sent to said logic control unit U, which comprises a processing program.

[0073] This processing program is based on a model of differential equations that exactly describe the dynamics of the railroad car R.

[0074] To generate a model it is necessary to establish a set of differential equations that define the physical model and the relative dynamic behavior.

[0075] It is proceeded by measuring the accelerations, which will then be used as input in the inverse differential equation system while at the output there are the characteristics of the components.

[0076] To validate the model, it is verified that the nominal parameters of the model determined by the *Rules Based* approach coincide with those obtained from the inversion.

[0077] If the mechanical characteristics detected at the output of the system coincide with the nominal ones, then the railroad car R has components that are still functioning, in the case in which the system returns values out of range, where the ranges are initially predetermined, then it will be necessary to replace, or maintain the component as its mechanical characteristics are deteriorating.

[0078] It is proceeded by steps, at the beginning some closed-loop elaborations are done in order to determine the parameters that characterize the differential equations, and which give rise to the optimal reference model, as well as to verify the validity of the differential equations and its inversion, namely, taken the nominal characteristics, the direct system of equations is solved, with the determination of the characteristic parameters using the *Rules Based* approach, and the output values are evaluated, checking that they are acceptable results, or if possible the theoretical results can be compared produced by the optimal model directly with the real data measured by the system.

[0079] Then, there is the inversion of the system, taking as input the output values from the direct system and inserting them into the inverse system, it is necessary to obtain the starting inputs at the output.

[0080] This allows verifying the differential equations that describe the system and it is subsequently possible to insert them in an open-loop model, which, by measuring the real values of the dynamics of the railroad car R, such as acceleration, gyroscopy, speed, returns through concurrent processing in the characteristics of the components in real time.

[0081] Therefore, the difference between the real behavior of the system and the expected one determined through the optimal model is analyzed in real time, as shown in figure 6, and the detachment threshold is defined, beyond which intervening with a direct maintenance intervention, on condition.

[0082] It is also possible to estimate the remaining life time of the physical component, i.e., to perform a prediction, basing this result using an approach on a degradation "*pattern*", obtained from the difference over time between the theoretical behavior of the system obtained from the optimal model, and the real measured behavior from the system, as indicated in figure 6, where the decision support processing element (DSS) estimates this time.

[0083] Based on the data to be monitored, these equations are inverted according to the parameter, after which the system is solved by entering the input data, in particular the displacements and the speed of the railroad car R.

[0084] At the same time, the simulation results are compared with the solution of the equations in which the displacements that the railroad car R should have had in ideal conditions have been inserted.

[0085] The differential equations have been written considering the X, Y, Z reference system described above.

[0086] The symbols used in the equations are shown below:

1) $yw1$: transverse displacement of the front wheelset;
2) $\psi w1$: Rotation around the vertical axis of the front wheelset;

3) *yw2*: transverse displacement of the upper mount;
4) *ψw2*: Rotation around the vertical axis of the rear wheelset;
5) *yb*: Transversal displacement of the bogie frame T;
6) *ψb*: Rotation around the vertical axis of the bogie frame T;
7) yb,d: Transversal displacement of the chassis C.

[0087] The following table shows all the parameters of the model to be able to elaborate the differential equations.

Massa of the mounted wheel set	$m_{w1.2}$
Mass of the frame of the chassis	m_b
Mass of the chassis	m_{bd}
Mass moment of inertia of the front and rear wheelset around z	$J_{zw1.2}$
Mass moment of inertia of the bogie frame around z	J_b
Longitudinal stiffness coefficient of the primary dampening	K_x
Transverse stiffness coefficient of the primary dampening	k_y
Longitudinal rigidity coefficient of the secondary dampening	K_{dx}
Transverse stiffness coefficient of the secondary dampening	k_{dy}
Longitudinal damping coefficient of the primary dampening	r_x
Transversal dampening coefficient of the primary dampening	r_y
Longitudinal dampening coefficient of the secondary dampening	C_{dx}
Transversal dampening coefficient of the secondary dampening	C_{dy}
Dampening coefficient of the anti-swaying dampening	*Cady*
Load per axle	*P*
Equivalent conicity	γ
Distance between the primary dampening attachment point and the bogie frame center of gravity	*a*
Distance between the attachment point of the primary suspension and the center of gravity of the wheelset	b
Average radius of the wheel	R_0
Longitudinal Kalker coefficient	f_{11}
Transversal Kalker coefficient	f_{22}
Track gauge	*2s = 1435 mm*
Semi-gauge	*s*

[0088] These constants may vary according to the dynamics equations used since each railroad car R has its own dynamics, some constants may be missing, for example if a damping is missing, this value is zero.

[0089] The general dynamics equations, which apply to any railroad car R, are shown below, and can be modified from time to time for any other railroad car R, by changing the values that characterize the railroad car R considered, i.e. stiffnesses, masses, damping and the like.

$$m_{w1}\ddot{y}_{w1} = -\frac{2f_{22}}{V}\dot{y}_{w1} + 2f_{22}\psi_{w1} - k_b y_{w1} - 2r_y\dot{y}_{w1} - 2k_y y_{w1} + 2k_y y_b + 2ak_y\psi_b$$

$$J_{Z,\,w1}\ddot{\psi}_{w1} = -\frac{2f_{11}S^2}{V}\dot{\psi}_{w1} - \frac{2f_{11}\Omega\gamma S}{V}y_{w1} + 2F_{Bo}S\psi_{w1} - 2b^2r_x\dot{\psi}_{w1} - 2b^2k_x\psi_{w1} + 2k_xb^2\psi_b$$

$$m_{w2}\ddot{y}_{w2} = -\frac{2f_{22}}{V}\dot{y}_{w2} + 2f_{22}\psi_{w2} - k_by_{w2} - 2r_y\dot{y}_{w2} - 2k_yy_{w2} + 2k_yy_b - 2ak_y\psi_b$$

$$J_{Z,\,w2}\ddot{\psi}_{w2} = -\frac{2f_{11}S^2}{V}\dot{\psi}_{w2} - \frac{2f_{11}\Omega\gamma Sy_{w2}}{V} + 2F_{Bo}S\psi_{w2} - 2b^2r_x\dot{\psi}_{w2} - 2b^2k_x\psi_{w2} + 2k_xb^2\psi_{bb}$$

$$m_b\ddot{y}_b = 2k_yy_{w1} + 2k_yy_{w2} - 4k_yy_b - 2k_{dy}y_b + 2k_{dy}y_{bd} - 2C_{dy}\dot{y}_b + 2C_{dy}\dot{y}_{bd}$$

$$J_b\ddot{\psi}_b = 2k_yy_{w1}a + 2k_xb^2\psi_{w1} - 2ak_yy_{w2} + 2k_xb^2\psi_{w2} - 2C_{\alpha dy}S^2\dot{\psi}_b - 4k_xb^2\psi_b - 4k_ya^2\psi_b$$

$$m_{bd}\ddot{y}_{bd} = -2k_{dy}y_{bd} + 2k_{dy}y_b - 2C_{dy}\dot{y}_{bd} + 2C_{dy}\dot{y}_b$$

[0090] From this model it is possible to obtain the various customizations, by way of example the application on a medium is shown without secondary dampening D2, the system of equation becomes:

$$m_{w1}\ddot{y}_{w1} = -\frac{2f_{22}}{V}\dot{y}_{w1} + 2f_{22}\psi_{w1} - k_by_{w1} - 2r_y\dot{y}_{w1} - 2k_yy_{w1} + 2k_yy_b + 2ak_y\psi_b$$

$$J_{Z,\,w1}\ddot{\psi}_{w1} = -\frac{2f_{11}S^2}{V}\dot{\psi}_{w1} - \frac{2f_{11}\gamma Sy_{w1}}{R_0} + 2F_{Bo}S\psi_{w1} - 2b^2k_x\psi_{w1} + 2k_xb^2\psi_b$$

$$m_{w2}\ddot{y}_{w2} = -\frac{2f_{22}}{V}\dot{y}_{w2} + 2f_{22}\psi_{w2} - k_by_{w2} - 2r_y\dot{y}_{w2} - 2k_yy_{w2} + 2k_yy_b - 2ak_y\psi_b$$

$$J_{Z,\,w2}\ddot{\psi}_{w2} = -\frac{2f_{11}S^2}{V}\dot{\psi}_{w2} - \frac{2f_{11}\gamma Sy_{w2}}{R_0} + 2F_{Bo}S\psi_{w2} - 2b^2k_x\psi_{w2} + 2k_xb^2\psi_b$$

$$m_b\ddot{y}_b = 2k_yy_{w1} + 2k_yy_{w2} - 4k_yy_b$$

$$_b\ddot{\psi}_b = 2k_yy_{w1}a + 2k_xb^2\psi_{w1} - 2ak_yy_{w2} + 2k_xb^2\psi_{w2} - 4k_xb^2\psi_b - 4k_ya^2\psi_b$$

$$m_{bd}\ddot{y}_{bd} = 0$$

[0091] In addition to the missing parameters, the values of the mechanical characteristics of the components also change and in particular, the system of differential equations is simplified and it is possible to invert the equations and find the parameters to be compared with the target values, the inversions of the differential equation system are shown below:

$$k_y = \frac{m_b \ddot{y}_b}{(2y_{w1} + 2y_{w2} - 4y_b)}$$

$$k_x = \frac{J_b \ddot{\psi}_b - \frac{m_b \ddot{y}_b}{(2y_{w1} + 2y_{w2} - 4y_b)} (2y_{w1}a - 2ay_{w2} - 4a^2\psi_b)}{(2b^2\psi_{w1} + 2b^2\psi_{w2} - 4b^2\psi_b)}$$

$$r_y = \frac{m_{w2}\ddot{y}_{w2} + \frac{2f_{22}}{V}\dot{y}_{w2} - 2f_{22}\psi_{w2} + k_b y_{w2} - \frac{m_b \ddot{y}_b}{(2y_{w1} + 2y_{w2} - 4y_b)}(-2y_{w2} + 2y_b + 2a\psi_b)}{-2\dot{y}_{w2}}$$

$$\gamma = \frac{\left(J_{Z,w1}\ddot{\psi}_{w1} + \frac{2f_{11}S^2}{V}\dot{\psi}_{w1} + \frac{J_b \ddot{\psi}_b - \frac{m_b \ddot{y}_b}{(2y_{w1} + 2y_{w2} - 4y_b)}(2y_{w1}a - 2ay_{w2})}{(2b^2\psi_{w1} + 2b^2\psi_{w2} - 4b^2\psi_b - 4a^2\psi_b)}(2b^2\psi_{w1} - 2b^2\psi_b)\right)}{PS\psi_{w1} - \frac{2f_{11}Sy_{w1}}{V}\Omega}$$

$$R_0 = -\frac{2f_{11}\gamma S y_{w2}}{J_{Z,w2}\ddot{\psi}_{w2} + \frac{2f_{11}S^2}{V}\dot{\psi}_{w2} - P\gamma S\psi_{w2} + \frac{J_b \ddot{\psi}_b - \frac{m_b \ddot{y}_b}{(2y_{w1}+2y_{w2}-4y_b)}(2y_{w1}a - 2ay_{w2})}{(2b^2\psi_{w1} + 2b^2\psi_{w2} - 4b^2\psi_b - 4a^2\psi_b)}(2b^2\psi_{w2} - 2b^2\psi_b)} = \frac{V}{\Omega}$$

[0092] In a fourth step, the simulation is validated.

[0093] The two simulations are compared in absolute value, the difference of the values instant by instant or the "delta", that is the deviation, if the delta of the two simulations is low, it means that the difference between the real system and the ideal or expected one is minimal, the system is behaving correctly and there are no anomalies regarding that parameter, otherwise, if the delta of the two simulations is high, the difference indicates that there is an anomaly on that parameter, it is also possible to determine the extent of the variation.

[0094] The model outputs are therefore:

- inverted parameter value;
- delta or deviation of the simulations.

[0095] It is possible to evaluate any parameter contained in the equations, if they are invertible, some of these are:

- gamma angle (conicity);
- springs stiffness (k);
- damping (r);
- wheel radius;
- lowering of the dampening.

[0096] Other parameters can be indirectly evaluated starting from these, such as:

- wheel wear;
- flange wear.

[0097] Also in this case the output data are stored in memory together with the other acquisitions.

[0098] When the entity of the anomaly exceeds a certain threshold, an alert is activated, which sends a signal to said maintenance management device 3.

[0099] Said maintenance management device 3 is capable of sending an alarm signal in order to activate the maintenance.

[0100] In particular, a reservation is made to the magazine of the spare parts necessary for the maintenance intervention, otherwise the automated purchase procedure is managed, a time is set for carrying out the maintenance intervention, the maintenance staff qualified/certified to perform the maintenance intervention, the equipment necessary for the maintenance intervention is booked, and augmented reality tools are used to provide support for the execution of the intervention.

[0101] As is evident from the above description, the advantages of the system object of the present invention are many, for example, the proximity of the processing to the data generating source, as it is performed directly on board of the railroad car R, the transmission of only the information connected to the 'detected anomaly, with the enormous reduction in the amount of data to be transmitted to remote storage and processing devices, reduced times of anomaly detection, immediate *early warning,* thanks to concurrent processing/in real time, during the running of the rolling stock, with direct communication to the maintenance manager, without going through the current intermediate stages, elaboration and operational/management, additional, the prediction of the condition of the equipment failure, the automatic correlation of anomalies detected directly to the maintenance intervention, without further additional operational/management steps, the automatic correlation of anomalies detected on board of the train due to any causes dependent/induced by the infrastructure state, the management of information related to failures for the validation of the parameters.

[0102] This allows the reduction of the machine downtime, the optimization of magazine stocks and the management of maintenance personnel and the reduction of maintenance management costs, due to interventions carried out after the occurrence of the fault condition.

[0103] The present invention has been described for illustrative but not limitative purposes, according to its preferred embodiments, but it is to be understood that modifications and/or changes can be introduced by those skilled in the art without departing from the relevant scope as defined in the enclosed claims.

Claims

1. System (S) for monitoring and predictive maintenance of the state of wear of mechanical components of a railroad car (R), responsible for driving dynamics, of the type comprising a chassis (C), two wheel-axles (A), a bogie frame (T) and dampening (D1, D2), comprising:

   a logic control unit (U) comprising a signal processing program,
   at least one plurality of sensors (1), which can be placed on said chassis (C), wheel-axles (A), bogie frame (T) and dampening (D1, D2), capable of detecting operation data of said railroad car (R) and sending corresponding signals to said logic control unit (U), said system (S) being **characterized in that** said signal processing program is capable of
   processing said signals so as to extract real characteristic data of said mechanical components of said railroad car (R),
   comparing said real characteristic data with nominal theoretical values in real time,
   emitting an alarm signal if the result of said comparison is outside a predetermined range of values.

2. System (S) according to the preceding claim, **characterized in that** said signal processing program comprises a system of differential equations capable of

   calculating an expected model of operation of said mechanical components, starting from said nominal values,
   calculating a real model of operation of said mechanical components, starting from said real characteristic data,
   comparing said real model with said expected model,
   calculating the deviation between the real model and the expected model,
   comparing the deviation with a predetermined range of values.

3. System (S) according to any one of the preceding claims, **characterized in that** said plurality of sensors (1) comprises accelerometers, inclinometers, gyroscopes and encoders.

4. System (S) according to any one of the preceding claims, **characterized in that** said operation data detected are vibrations, triaxial accelerometry, triaxial gyroscopy, triaxial inclinometry, speed and distance traveled by said railroad car (R).

5. System (S) according to any one of the preceding claims, **characterized by** comprising an acquisition data device (2) capable of receiving said signals detected by said plurality of sensors (1) and digitizing and converting said signals.

6. System (S) according to any one of the preceding claims, **characterized by** comprising a predictive maintenance management device (3) of said railroad car (R), capable of receiving said alarm signal and activating maintenance

operations.

7. System (S) according to any one of the preceding claims, **characterized by** comprising an energy recovery system capable of taking vibrational, and/or acoustic, and/or electromagnetic, and/or solar, and/or photovoltaic, and/or wind and/or micro-wind energy and converting it into electrical energy.

8. Operation method of a system (S) for monitoring and predictive maintenance of the state of wear of mechanical components of a railroad car (R), of the type comprising a chassis (C), two wheel-axles (A), a bogie frame (T) and dampening (D1, D2), **characterized in that** it comprises the following steps:

a. detecting operation data of said railroad car (R) and sending corresponding signals to said logic control unit (U);
b. carrying out a pre-processing on said signals, such as digitization and conversion;
c. processing said signals to extract real characteristic data of said mechanical components of said railroad car (R);
d. comparing said real characteristic data with nominal values of said mechanical components, in real time;
e. checking if the result of said comparison falls within a predetermined range of values;
f. emitting an alarm signal if the result of said comparison is outside said predetermined range of values;
g. storing said pre-processed signals and said compared data in said step *d.*

9. Method according to the preceding claim, **characterized in that** said it comprises the following step:
h. estimating the time interval in which the monitored mechanical component can pass through an anomaly condition, in order to manage the predictive maintenance activities related to it.

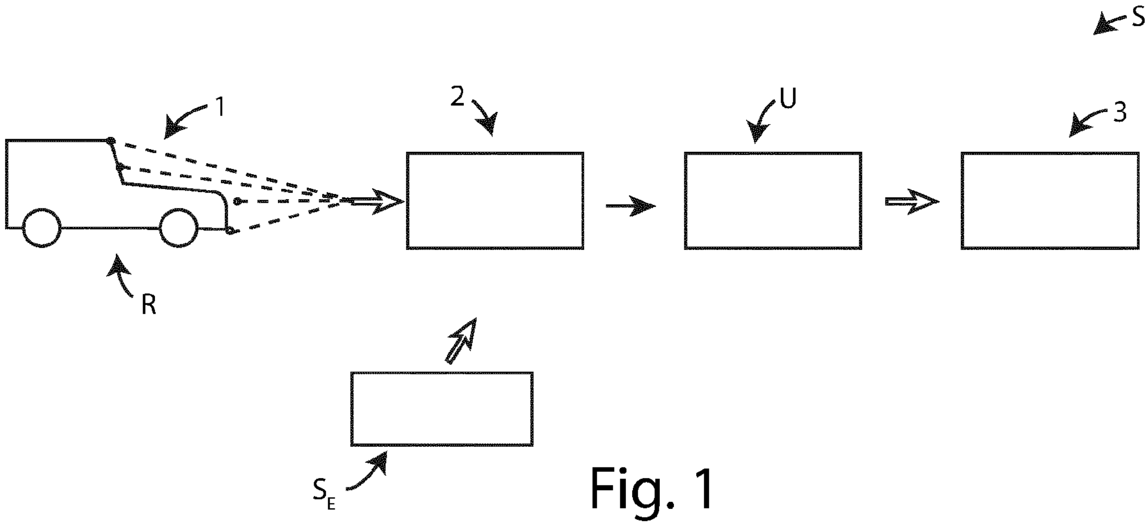


Fig. 1

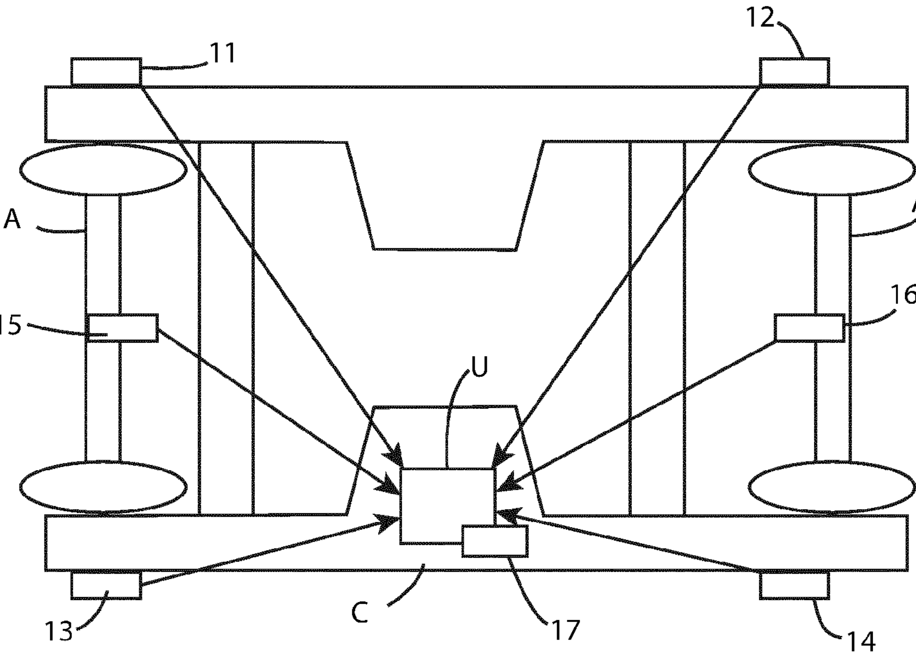


Fig. 2

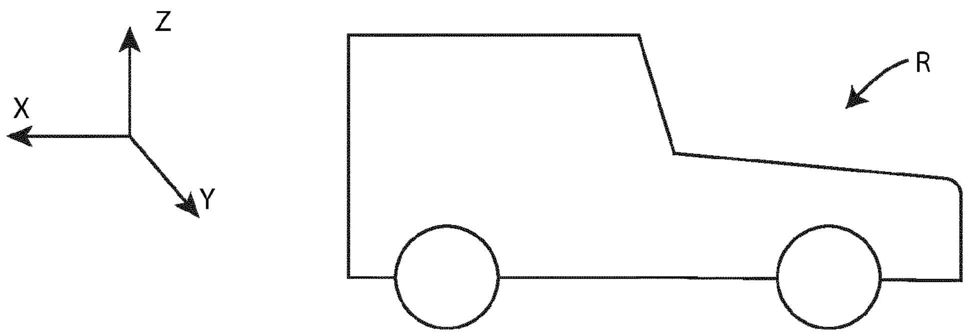
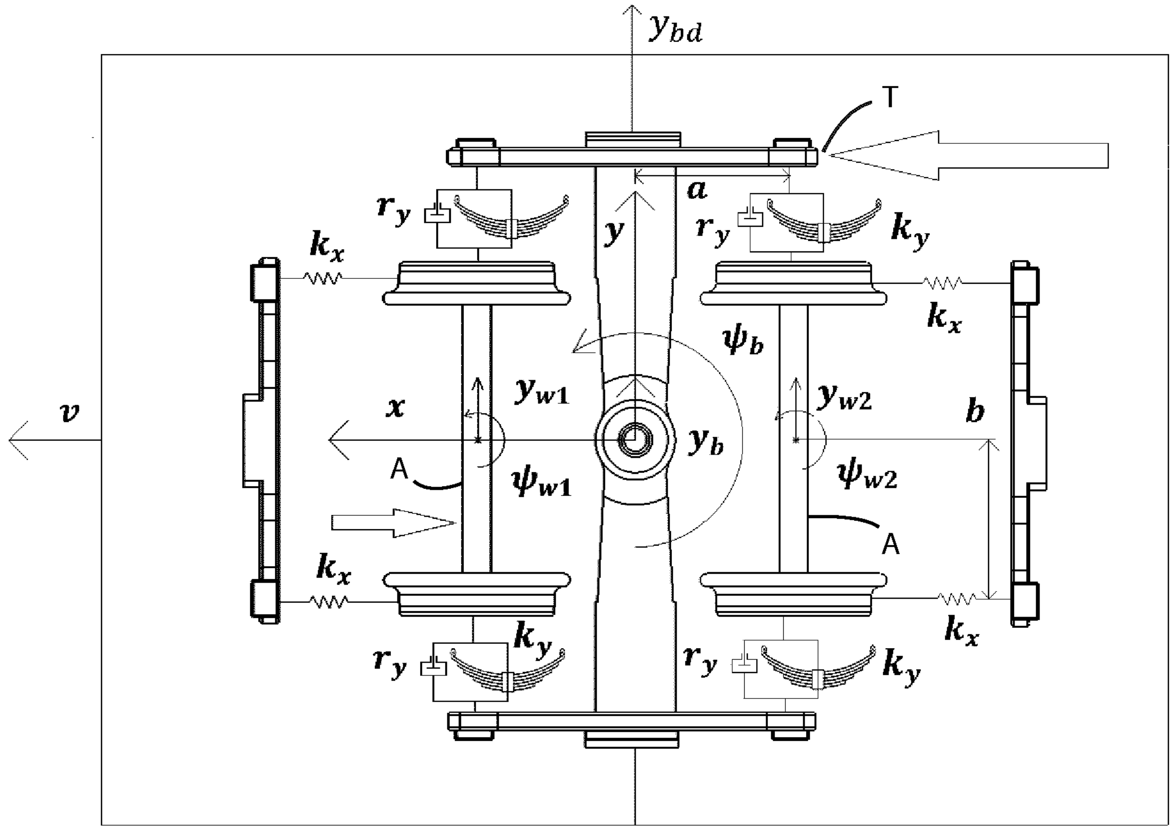


Fig. 3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r_y
y
r_y
k_y
k_x
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ψ_b
v
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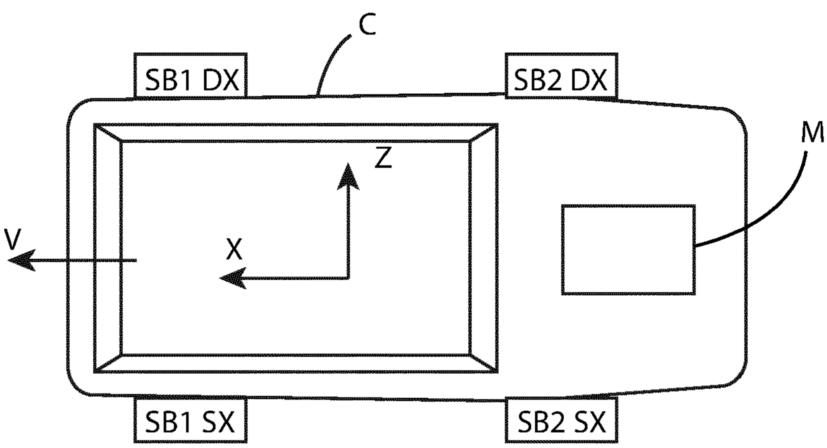
b
y_b
A
ψ_{w1}
ψ_{w2}
A
k_x
k_x
k_y
r_y
r_y
k_y

Fig. 4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SB1 DX
SB2 DX
M
Z
V
X
SB1 SX
SB2 SX

Fig. 5

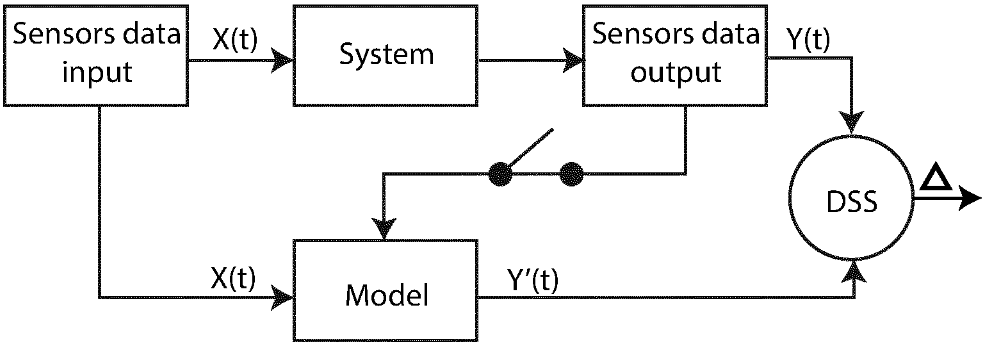

Fig. 6

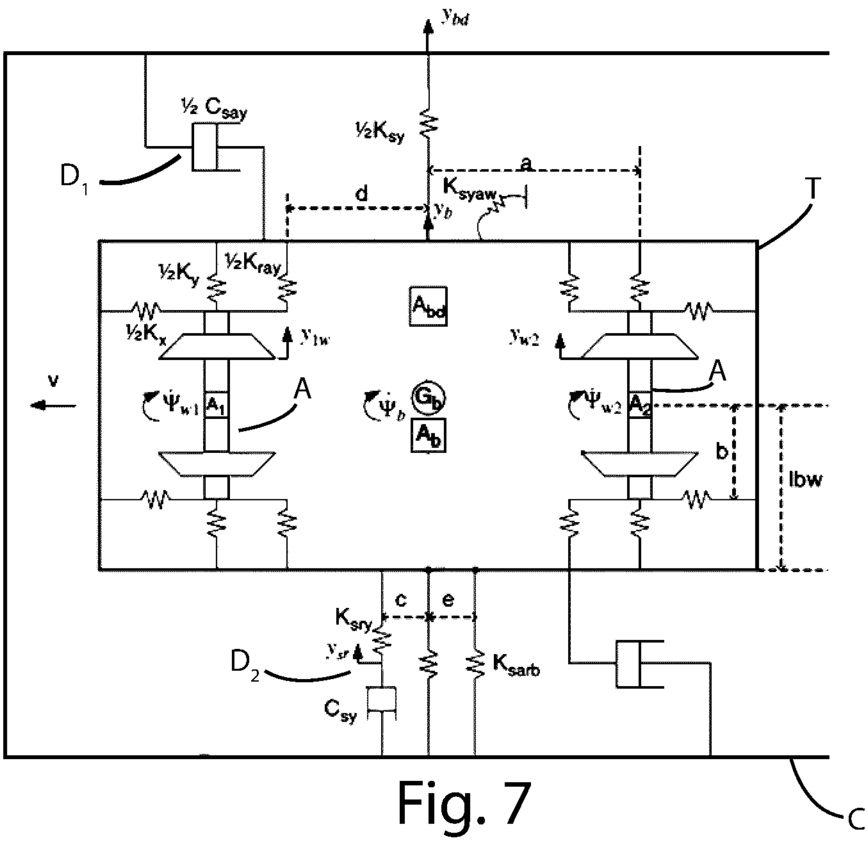

Fig. 7

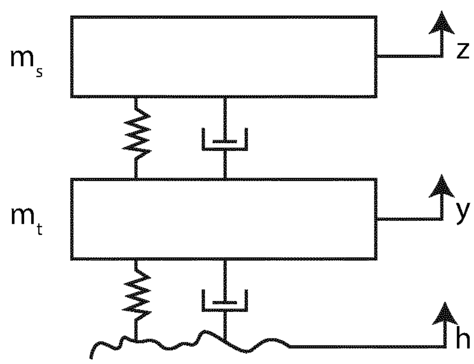

Fig. 8

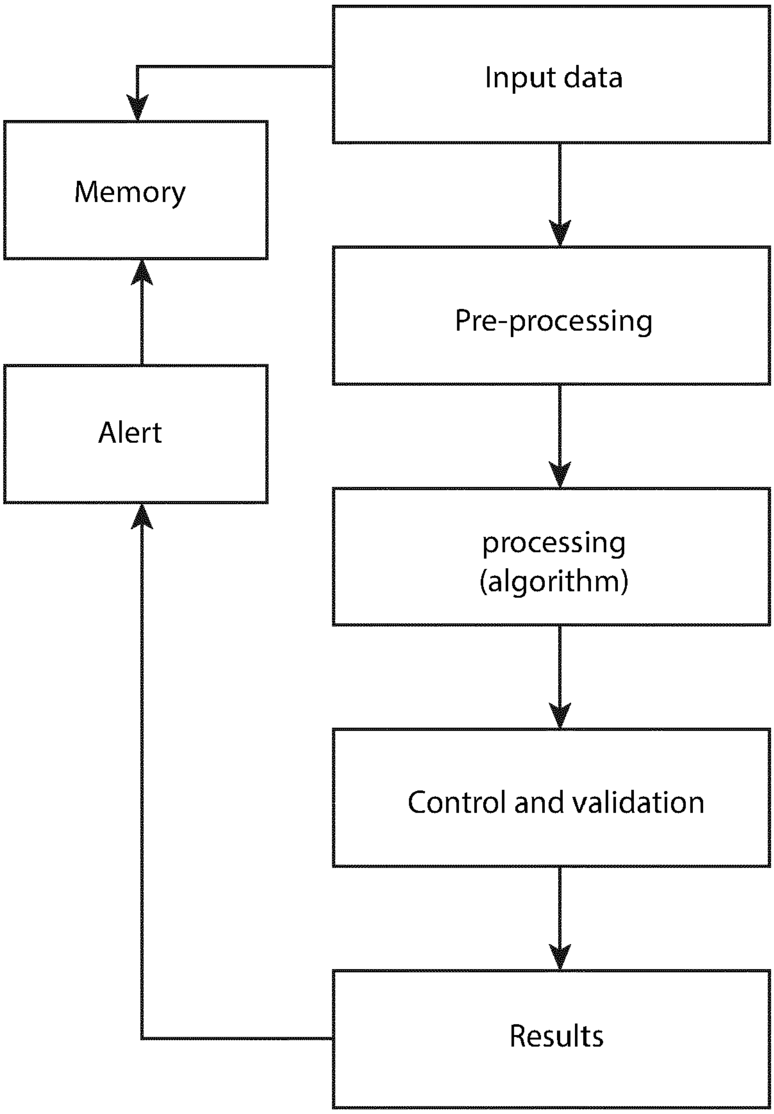
Input data
Memory
Pre-processing
Alert
processing
(algorithm)
Control and validation
Results

Fig. 9

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EUROPEAN SEARCH REPORT

Application Number
EP 21 21 0973

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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	19 April 2022	Lorandi, Lorenzo

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