Solar Wireless Sensor Nodes for Condition Monitoring of Freight Trains

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***Abstract*— The objective of this work is to present the design and testing of a Wireless Sensor Network, powered by solar energy, to be installed on freight trains with the purpose of performing on-board monitoring operations. A complete Wireless Sensor Network requires a certain number of Wireless Sensor Nodes, installed in significant points of a vehicle, provided with sensors and capable of elaborating raw data, transmitting them via wireless network as synthesis information to an on-board control unit. The on-board control unit periodically communicates the data gathered from different sensors to a ground central control unit through the Internet. Each Wireless Sensor Node needs to be powered independently. To achieve this purpose a small solar panel was used to provide the Wireless Sensor Node with the necessary amount of energy. Integrated circuits were designed for power management, acquisition, elaboration and wireless transmission of data and analyzed in terms of performances and energy consumption. The communication protocol between the Wireless Sensor Node and the control unit was first laboratory-tested and finally the whole system was installed on a real wagon, and on-field tests were conducted for a period of almost one year.**

***Index Terms*— Freight Trains, on-board monitoring, wireless sensor nodes, energy performances, solar energy, wireless sensor networks, on-field tests.**

I. Introduction

CURRENTLY, last generation high-speed trains for passengers are equipped with a number of sensors (accelerometers, temperature sensors, strain gages, etc.) that allow to continuously monitor the main safety parameters and to implement, in some cases, condition-monitoring strategies. For these applications, sensors are generally installed during train assembly and are integrated into the complete system.

A similar approach is not possible for freight trains: wires connecting different wagons are not a feasible solution due to the need of reassembling the convoy for each new trip. For this reason, any sensing system for freight vehicles requires an independent source of energy for every single wagon.

In recent years, the need of improving the safety of freight trains as well as maintenance requirements increased significantly. Knowledge of the conditions of the wagon allows for preventing accidents and for planning condition-based maintenance, thus avoiding high costs caused by an unexpected stoppage of the entire line. Moreover, monitoring drive quality is very useful to associate accountability for transportation and delivery of fragile goods in supply chain. Furthermore, especially for freight convoys, the possibility to know the exact position of each wagon at any time can significantly increase the efficiency and the performance of this kind of transportation system [1]. In general, two main approaches can be adopted when dealing with train condition monitoring: wayside monitoring systems and on-board monitoring systems [1], [3]. The first solution is already implemented in many railway lines. Hot Axle-Box Detectors (HABDs, [4]), for the evaluation of bearing faults, and Wheel Impact Load Detector (WILDs, [1]), able to identify wheel tread defects by measuring forces/accelerations transmitted to the rail by the train passing, are both largely adopted [1], [4], [6]). Other specific autonomous wireless sensors along the line are able to retrieve energy from the passing train by means of magnetic levitation energy harvester [7], [8]. Anyway, to perform a real-time continuous monitoring using wayside monitoring systems would require the installation of a huge number of devices over the entire line. This solution appears not feasible in terms of costs, and the desired level of performance has not been reached yet [1], [6].

In the context of onboard systems for freight trains, the main problem to be solved is providing the energy needed to power monitoring sensors. In fact, they shall be installed in harsh environments (such as the axle-box of freight wagons), where a low-voltage energy source is usually not available. Also in this case, two main approaches can be adopted:

- wired instrumented wagons/bogies/wheelsets, with a single electric power unit ([1], [9]–[14]);
- autonomous wireless sensors nodes, each having its own source of energy.

With the first approach, the energy required to power the condition-monitoring system is obtained by a combined system of batteries and a generator that transforms the energy available on a wagon (mechanical, solar, etc.) into electric energy [9]. The power unit is set in a specific position of the vehicle according to the source used: near the wheel, in correspondence of the axle-box cover, ([9], [10], [12]); or near the suspensions ([13], [14]). In these systems, the sensors and the acquisition systems are connected to the power unit by wire, while the diagnostic information gathered form sensors is then uploaded/sent to a server. The device designed by Nagode *et al.* ([13], [14]) exploits the relative motion between wagon and unsprung masses and gathers this energy by means of an electromechanical system placed inside the spring coil

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of the suspension. During the last two years, MercItalia Rail Company, in Italy, adopted a similar solution for a fleet of 350 wagons allowing to monitor different quantities as axle-weight, GPS position, bearing temperature, impact acceleration, etc. In this case the energy source is a electromechanical generator connected to the axle-box [11]. Within this group, it is possible to include also instrumented wheelsets for measuring contact forces [15]–[18]).

From one side, this approach requires a time-consuming and expensive transformation process for the instrumentation of the wagon and, typically, maintenance costs and time are higher than those for a traditional wagon. On the other hand, this approach allows having a great quantity of energy available and different types of sensors can be connected simultaneously.

The second approach, based on autonomous wireless sensor nodes, has been developed over the last few years but is not yet largely adopted on freight trains [1]. Some commercial sensors for condition monitoring of rail vehicles have been industrialized by companies working in the railway sector, i.e. the European wagon company VTG, Amsted Rail, SKF. Other wireless sensors have been designed and tested starting from research studies. In most cases, these devices are conceived to measure particular quantities and need to be connected to specific parts of the vehicle. Nexiot Intermodal [19] is a sensor installed on the car body which is capable of measuring wagon position and shock events. SKF Insight Rail [21], homologated for passenger trains, measures bearing vibration and temperature. Perpetuum system [19] is powered by an electromagnetic vibration energy harvester and, consequently, is set in correspondence of the axle-box. In [23], a hollow shaft sensor node with acoustic sensors was developed for detecting wheel defects, such as cracks, but it was only laboratory tested.

Some recent papers analyzed sensor nodes developed specifically for railway applications and studied different ways to reduce energy consumption in wireless transmission system [40], [52]–[56].

In [24]–[29], the authors developed low-cost, low-power sensor nodes powered by different types of vibration energy harvesters (inductive, capacitive, piezoelectric, electromagnetic) for freight-wagon derailment detection. In particular, piezoelectric harvesters are very commonly used in the rail industry thanks to their ability in transforming mechanical energy directly into electric power ([30]–[32]). The total amount of recovered energy is usually not very high (up to 10 mW according to a recent review on the use of piezoelectricity for energy recovery from ambient vibrations [33]).

All these sensors, due to the necessity to set them in specific positions on the vehicle to recover the energy of the specific source (i.e. mechanical vibration of the axle box) cannot be used for monitoring all the quantities (i.e. bogie acceleration) because their position cannot be changed.

On the other hand, a lower number of wireless sensors, developed in recent years, are configurable to measure different parameters of various subsystems of a railway vehicle. IONX is a sensor, developed by the US-based company Amsted Rail, composed by a Communication Management Unit (CMU) and a certain number of Wireless Sensor Nodes [22]. The nodes, powered by lithium batteries, measure, elaborate data and send them to the CMU, which is responsible for transmitting information to a central server via GSM network. The IONX sensor nodes are guaranteed for 10-year battery life; anyway, it is well known that battery life depends on the consumption, that varies in function of the number of data acquisitions and operations performed. IONX is a commercial system designed to work in harsh environments with the purpose of monitoring the location of the wagon with a real-time approach. The objective of this device is to reduce the costs related to logistics [34].

Another device, created by ETH Zurich and adopted for commercial use, is NEXIOT. The system was adopted by VTG first, and is now able to monitor the position of almost 2.000 wagons, out of a total VTG fleet of 80.000 wagons; the objective is to reach the full implementation of this device by 2020 [35]. This system, which uses a combination of a rechargeable battery and a small solar panel, can perform three main operations: localization of the wagon by means of the GPS system, maintenance scheduling giving the mileage of each monitored wagon, and shock monitoring, based on the measure of acceleration peaks [36].

In [37], the authors designed a Wireless Sensor Node for measuring vertical and lateral acceleration of the car body; each sensor is powered by a 3.6 V lithium battery. A similar system was proposed in [38]: this system was able to perform a continuous monitoring of vehicle for almost 1400 km and a total duration of almost 90 hours. It was able to monitor the temperature of brake blocks, the operating pressure of the brake system and the vehicle acceleration under critical conditions (harsh slopes in the alpine railways) creating an important database for future comparisons. Power is distributed throughout the system by a cable network connected to a battery. The same authors developed a hybrid (cabled + wireless) system able to monitor both the temperature of brake blocks and the temperature of bearings [39].

The current research project has been funded by the Railway Joint Research Center group, which includes the main railway operators in Italy such as Trenitalia, RFI, ABB, Hitachi Rail Italy, Bombardier Transportation, Ansaldo STS and Faivelay, with the aim of developing and testing wireless autonomous sensor nodes for condition monitoring of freight vehicles. The sensor developed within this research is a completely autonomous, easy-to-assemble, and affordable wireless sensor node capable of working with different subsystems of a freight wagon (wheelsets, bogies, car body, brakes, suspensions, etc.) and of measuring different quantities (acceleration, temperature, pressure, etc.). The main requirements of the Wireless Sensor Nodes for this application are:

- autonomous source of energy;
- wireless communication with a central control unit (installed on board);
- capability of acquiring raw data from digital sensors, elaborating them and generate easy-to-read information on the structural health of the wagon.

In particular, for the first field testing campaign, the nodes were dimensioned and set to identify a growing crack in a

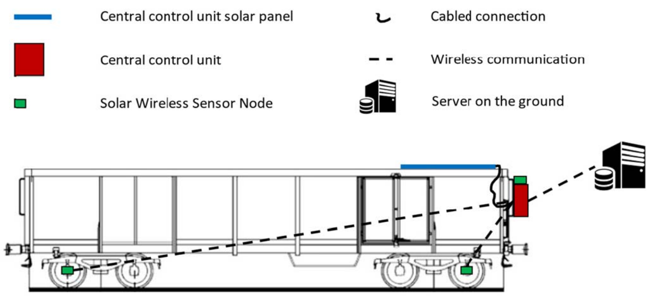


Fig. 1. Scheme of the wireless sensor network for freight train.

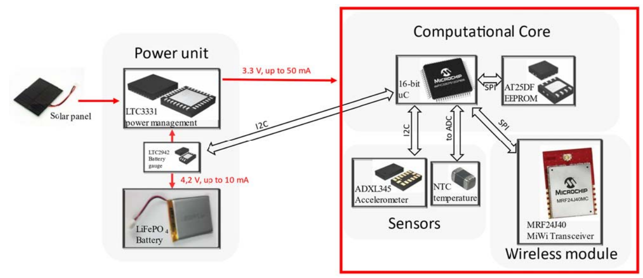


Fig. 2. Node layout.

wheelset, starting from acceleration measurements carried out in correspondence of the axle box, according to an algorithm developed in previous researches [59]–[61].

The designed nodes embed sensors and a microprocessor and are equipped with low-consumption, wireless transmission systems, powered by an autonomous system based on a combination of rechargeable battery and solar panels.

With respect to the configurable devices capable of measuring different quantities and parameters described in previous papers [22]–[36], this sensor is provided with a small solar panel for the recharge of the battery, which is completely integrated into the sensor box: this allows increasing the life of the sensor and/or the quantity of operations it can do. Among the possible power sources available on board of a freight train for energy harvesting, solar energy has been chosen as the most appropriate source of energy for its abundant presence in all outdoor applications and because it allows placing the sensor in any position on the wagon (boogie, axle-box, car body, etc.) according to the quantity to be measured. This choice is justified also by the fact that previous studies has demonstrated that solar source is the most affordable energy source with respect to mechanical vibrations and/or wind energy generated by the motion of the vehicle [62].

The sensors have been tested both in laboratory, to verify efficiency and mechanical fatigue, and in field tests on a Y25 freight wagon in commercial service, for a period of more than 10 months (and it is still correctly working). The Wireless Sensor Node developed has demonstrated to be able to correctly work in that harsh environment.

According to the global project, each wagon is equipped with different nodes in communication with an on-board control unit, forming a Wireless Sensor Network able to collect the wagon geographical coordinates and all the diagnostic data coming from the sensor nodes. Such data are sent periodically or in case of critical conditions (when conditions are specified), to a ground, centralized control unit (server). A scheme of the data information flow is shown in Fig. 1.

This article is organized into a total number of 7 sections.

The next section describes the integrated circuit that allows managing the power distribution to each component of the node. The on-board control unit is presented in section 3. Section 4 contains the mechanical assessment of the node by means of laboratory tests. In section 5, the Wireless Sensor Node is tested in terms of energy performances. Section 6 presents the results obtained during the field-testing campaign, and in the last section the conclusions are drawn.

II. Design of the Wireless Sensor Node

A. PCB Design

Fig. 2 illustrates a block diagram of the node layout. The power source, that is the solar panel, is connected to the Integrated Circuit (IC), responsible for the on-board power management. The IC manages the charge of the battery using solar energy and provides a stabilized supply voltage to the microprocessor and to all the sensors installed on the board.

After collecting and analyzing data from the sensors, the microprocessor is able to transmit the synthetic values of these measures to a nearby on-board control unit via a wireless transmission system.

Referring to the node layout shown in Fig. 2, the main components of the custom designed board are listed below.

1) *Power management IC*
The on-board power management functions are implemented through the LTC3331 IC. This component is a Nanopower DC/DC Buck-Boost with Energy Harvesting Battery Charger. The LTC3331 can manage the battery charge as a function of the power coming from the solar panel. In order to greatly extend the battery life, a 10 mA shunt battery charger is integrated into the LTC3331, limiting the maximum charging current. The output power of LTC3331 to supply the system is 3.3 V limited to 50 mA, thus guaranteeing a power output of 165 mW.
2) *Battery* The battery chosen for the project is a 3.7V Lithium Polymer rechargeable battery with a capacity of 2Ah. This battery technology allows to have the highest level of energy/power density and hence it is possible to minimize the battery size both in terms of dimension and weight. The battery is $44 \times 72 \times 7$mm and weights 40g.
3) *Battery gauge* The battery gauge is used to measure the current flowing through the battery and its voltage. These measures are fundamental to estimate the battery State of Charge (SoC).
4) *Microprocessor* The chosen model for microprocessor is the DSPIC33EP512GP806. It is a 16-bit dsPIC (digital signal microcontroller) that allows to implement functions of digital signal processing, with 512 kB of flash memory.

5) *Accelerometer* For the on-board acceleration measurement, the 3-axis ADXL345 digital accelerometer has been chosen. It is a 13-bit resolution measurement with a full scale up to $\pm$ 16g.
6) *Bus Voltage* The measurement of the DC voltage on the bus of the LTC3331 has also been considered. This value can be acquired directly with the microprocessor ADC using an appropriate voltage divider and can be used to analyze the status of the system.
7) *Temperature sensor* Besides the temperature sensor embedded in the battery gauge IC, an additional thermal probe has been added on the board in order to measure the temperature in specific points (not necessarily close to the battery gauge IC) or possibly far from the PCB with a proper wiring.
8) *Communication module* Once all the measures have been gathered and the microprocessor has performed the proper analysis on the data, it is possible to send some synthetic values to the master control unit. For this last action, a 2.4GHz IEEE Std. 802.15.4™A compliant RF Transceiver has been selected, the Microchip transceiver MRF24J40MC, in order to be able to use one of the following Proprietary Wireless Networking protocols: ZigBee®, MiWi™. The chosen transceiver allows also for a delocalization of the antenna, to maximize the transmission range and reducing the shielding effects due to any kind of enclosure. Among the different protocols available the ZigBee®has been chosen. In fact, it is cheaper than BLE and it has an expected higher data rate than LoRa and SigFox. With respect to WiFi protocol it guarantees lower consumption. Moreover, since the MiWi™protocol has been developed by Microchip, it guarantees a better integration with the microcontroller adopted.
9) *Data storage* Finally, in order to save in a permanent memory storage device some configuration data, a 4 Kbit Serial Electrically Erasable Programmable Read-Only Memory (EEPROM) was chosen, paying particular attention to the low power consumption, especially in stand-by mode.

In order to minimize the mean consumption of the node, the electronic board was programmed to alternate two different working modes:

- Full-power mode: the microcontroller runs at its full capability, acquiring data from the accelerometer, performing data analysis and sending the results through the wireless protocol.
- Sleep mode: the device enters in a very low-power consumption mode, minimizing the use of the battery. When no operation is required for the node, the sleep mode is activated, allowing for a consistent energy saving.

The logic adopted during this research is to alternate Full power mode and Sleep mode at constant time intervals. The total duration between the beginning of a full power mode and the beginning of the next one is called duty cycle, and can be set during the programming of the electronic board (for the in-line tests, it will be set to 30 minutes). The duration of a full power mode operation (about 2.5 seconds) is equal to the minimum time required to the node to perform the following operations:

- acquisition: acceleration data in the three spatial directions are acquired for a time window of 1s. The sampling frequency adopted is 400Hz, so that the total number of points acquired are 512. Data are stored into the buffer memory;
- processing: the microprocessor elaborates the raw data coming from sensors creating summarized information. The Fast Fourier Transform (FFT) is computed on the signal giving as output 256 complex lines of the spectrum;
- transmission: the elaborated data are transmitted cable-free to the on-board central control unit.

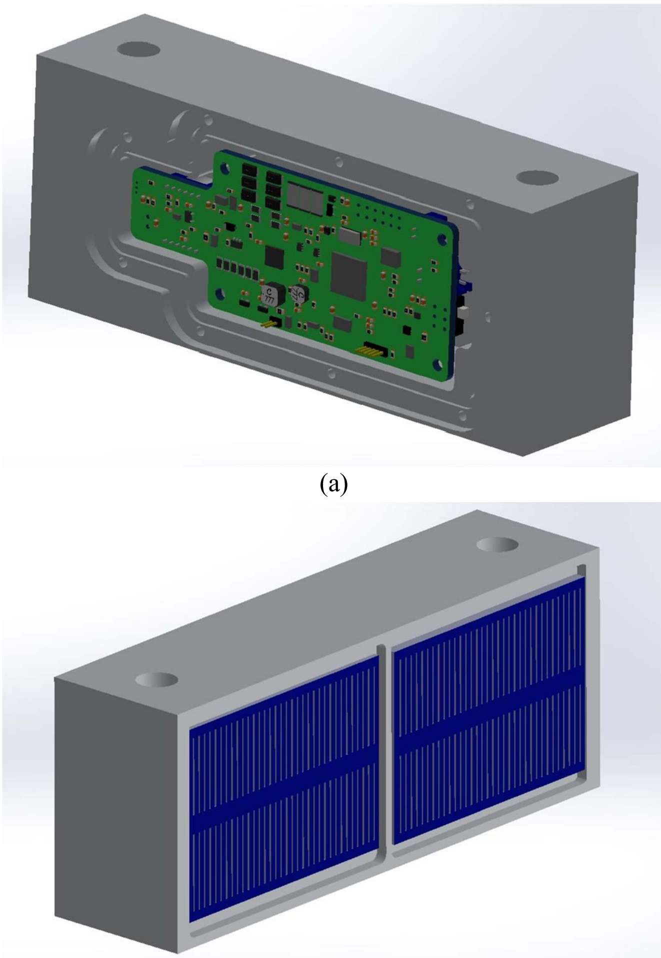
Fig. 3. Photo of the board manufactured.

B. Mechanical Design

To properly protect the PCB, a stainless steel box was designed. The shape and dimension of the box are chosen according to the necessity of housing two small solar panels that ensure around 1W of total harvested energy. A commercial solution was adopted for solar panels, each with a dimension of 71.50 mm x 57.00 mm.

Two separated parts are created. On one side (Fig. 4-a), the electronic board is fixed to the case by means of spacers and it is protected from external agents by a cover. A rubber gasket also guarantees protection against rain and humidity. On the opposite side (external side, due to the need to be exposed to direct sunlight), two compartments are created to house the solar panels (Fig. 4-b).

The whole system is designed to be fixed to the vehicle by means of anti-vibration bobbin mounts: these rubber elements can be screwed in the box and can be easily interfaced



(a)

(b)

Fig. 4. 3D view of the node-box realized: compartment for electronic board (a) and solar panels (b).

with different parts of the vehicle. Moreover, the function of the rubber elements is to filter out high frequency vibration components, protecting the electronic board from impacts and high accelerations in vertical direction. This solution makes the node suitable to be applied in different parts of the railway car (car-body, bogie, axle-box, etc.).

A 3D view of the final design of the box is shown in Fig. 4.

The total cost of the realized node (including the battery, the small solar panel, the PCB and the external case) is around 250 €.

III. Description of the Control Unit

The on-board control unit, developed by Ansaldo STS [58], is used to collect data coming from the nodes installed on the train through wireless communication. The information is then sent to a server by means of an internet connection supported by a GSM system. A block diagram of the communication layout of the control unit is shown in Fig. 5.

The control unit is powered by a solar panel. Morevoer, an electric motor mounted on the axle box of the train is used as a generator providing aid in powering the control unit when the vehicle is in motion and it is also capable to detect the vehicle speed. The line voltage, produced by the

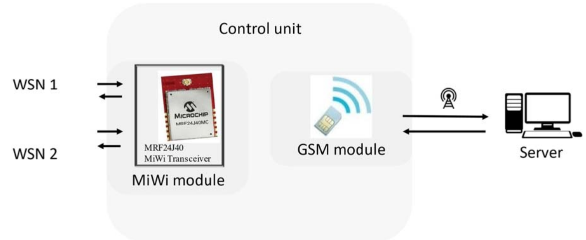


Fig. 5. Control unit communication layout.

electric generator when the vehicle is moving, is connected to two infrared emitting diodes connected in inverse parallel. The voltage so obtained is used to drive a single phototransistor output. In this way, a square wave is obtained. The frequency of the square wave is twice the line voltage, making it possible to detect the movement of the train and its speed.

When the train starts moving, the control unit activates. When the train is moving, the duty cycle is equal to 70' (composed by 30' of sleeping mode and 40' of full power mode), otherwise, it is equal to 24 hours.

When the control unit is on, it waits for the data coming from the Wireless Sensor Nodes. Each Wireless Sensor Node sends to the control unit an acknowledgment; if it does not receive any answer from the control unit, the Wireless Sensor Node goes back into sleep mode, otherwise, the control unit sends the vehicle speed data used by the Wireless Sensor Node to calculate the Frequency Response Function (FRF). Finally, the Wireless Sensor Node sends back to the control unit the overall data. The control unit knows how many Wireless Sensor Nodes are mounted on board and their own, specific ID number. When all the Wireless Sensor Nodes have sent their messages, the control unit sends the collected data to the server and goes into sleep mode again. Otherwise, if the control unit does not receive messages from all Wireless Sensor Nodes, it waits for half an hour, sends the received messages to the server and then, goes back into sleep mode.

IV. Fatigue Tests

The main objective of fatigue tests is to verify the resistance of all mechanical components over a high number of cycles considering vibrations equivalent to those of the real case.

The Wireless Sensor Node is tested on an electrodynamic shaker and monitored by means of an accelerometer. The input imposed by the shaker has been defined considering the worst position for the sensor from the vibrational point of view, which corresponds to the axle-box. For this reason, a random time history having the PSD (Power Spectral Density) of vertical acceleration measured in correspondence of the axle-box of a real freight train, when running at its maximum speed 33 m/s, has been adopted.

To verify the integrity of the box and its foot anti-vibration mounts, an accelerometer was used, which allowed checking that the natural frequency was constant. A shift in natural frequency is often a sign of concentrated damage of some mechanical components.

The total duration of the test was defined to reach a total number of cycles equal to 2 by 10^7, which correspond to the

Fig. 6. Fatigue tests: setup of the solar node on electro-dynamic shaker.

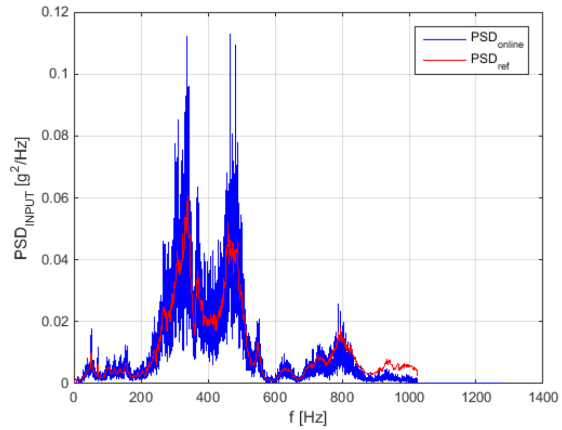


Fig. 7. Fatigue tests: input reference PSD (red line) and real PSD (blue line) measured on the shaker.

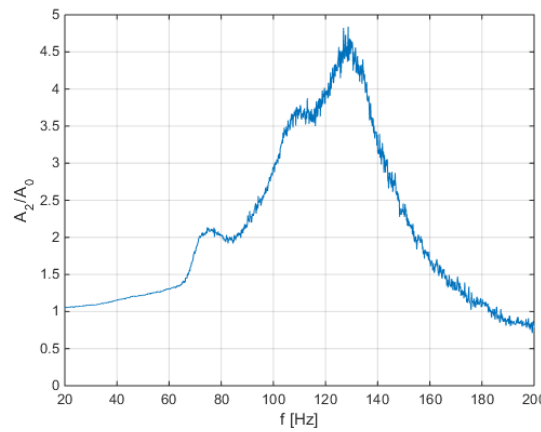


Fig. 8. Fatigue tests: FRF of solar node around resonance peak [20-200] Hz.

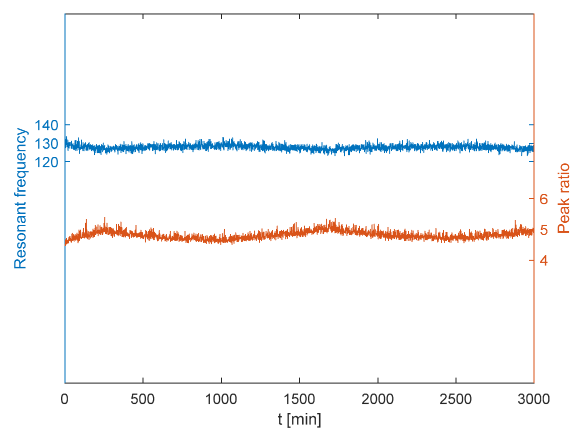


Fig. 9. Fatigue tests: solar node resonance frequency and peak ratio.

natural frequency of the node-box suspended on its mounts (about 130 Hz), for a total of 50 hours.

A. Experimental Setup

The experimental setup was composed by the following devices:

- electromagnetic shaker with closed loop control. It is able to generate a random input signal with a given PSD, with a maximum frequency resolution of 1 Hz;
- two accelerometers (PCB, full scale ±50 g). One was directly connected on the shaker to close the loop of the shaker itself, the data being acquired to know the exact input acceleration given to the nodes, while the other was placed on the top of the node.

A picture of the setup is shown in Fig. 6.

B. Experimental Results

The FRF (Frequency Response Function) between the vertical acceleration measured on the sensor box and the acceleration imposed by the shaker is computed. The objective is to verify the constancy of the FRF shape. A synthesis graph showing the peak value of the FRF and the corresponding frequency is then plotted as a function of time in Fig. 9. A constant value of frequency in correspondence of peaks reached guarantees the mechanical integrity of the node's structure.

Fig. 7 shows a comparison between the Power Spectral Density given in input (red line) and the corresponding PSD generated by the shaker (blue line): it is possible to see that the shaker is able to reproduce the given reference very well up to high frequency values of 600-700 Hz.

Fig. 8 shows an example of the FRF evaluated for a 60s-long time window, in the 20Hz-200Hz range: it is possible to see that the peak value is reached at about 130 Hz.

This calculation is repeated for all the consecutive time-windows. The results of the 50 hours long test are shown in Fig. 9, both in terms of resonant frequency and correspondent resonant peak value, as function of time, for each minute of testing.

We observe a certain variability on the frequency, due to the fact that the input is random even if the PSD is constant: for this reason, the energy content in each frequency band is determined by statistical method, but it is not perfectly constant in time.

An oscillation is observed, with a period of 24h, also in the trend of the peak. In this case, the variation is probably related to temperature changes during day and night, influencing the mechanical properties of materials like rubber.

In conclusion, both frequency and peak values are almost constant along the whole test and the structural integrity of the node is guaranteed after 50 hours of test under the maximum load applicable to the system.

V. Energy Performances

This section investigates the energy performance of the electronic board, as well as the performance of the battery and the solar panel. Four laboratory tests have been conducted to characterize the energy consumption of the node:

- instantaneous power consumption in full-power mode;
- mean power consumption in sleep mode;
- solar panel performance;
- real-like working conditions over a period of 7 months.

The following operational settings of the node have been adopted for all the tests:

- acquisition of the acceleration in the three directions;
- evaluation of FFT and RMS value for the three signals;
- duty cycle of 30 minutes.

The duty cycle has been chosen in order to guarantee the stopping of the wagon if the measured values go beyond the safety threshold.

Anyway, it is important to underline that the developed node allows to set different options in terms of operating modes (time-window, duty cycle, etc.), according to the selected condition monitoring activity.

A. Instantaneous Power Consumption in Full-Power Mode

Firstly, the instantaneous energy consumptions of the electronic board are tested in full power mode, by means of laboratory test performed with a NI9239 National Instrument module (NI laboratory test). The NI9239 module allows to acquire analog voltage signal using a very high sampling frequency (up to 52 kHz) [63]. A shunt resistance, connected in series, allows to know the current in the battery. The product of voltage by current gives as a result the power, as $P = Vi$. The total duration of full-power mode operation is about 2.5 seconds. For the rest of time inside a duty cycle the node works in sleep-mode. The energy consumption in sleep mode falls in the range of measure uncertainty of the test setup (with NI system) and cannot be correctly measured by this test. For the estimation of sleep mode consumption see Chapter V, section B.

Fig. 10 shows in detail the battery power consumption of the node during the full-power mode operation, measured by means of the NI setup previously described. The mean power consumption of each phase is highlighted by the symbol ‘x’. In grey the mean value for sleep mode, in black the mean power consumption for the full power mode, furtherly divided into: Acquisition/Processing in green and Transmission in red. The peak value of power consumption is obtained during data transmission and highlighted with a red star: its value is about 360 mW. The detailed consumptions related to the full power operation mode, estimated with NI acquisition system, are summarized in Table I.

As expected, from the energetic point of view, the most expensive phase is the wireless transmission with a peak consumption that reaches a value of 360 mW. The correct operation of the node during data transmission is ensured by the battery. The battery can provide a constant voltage even during the peaks of power consumption, which the harvester alone would not guarantee.

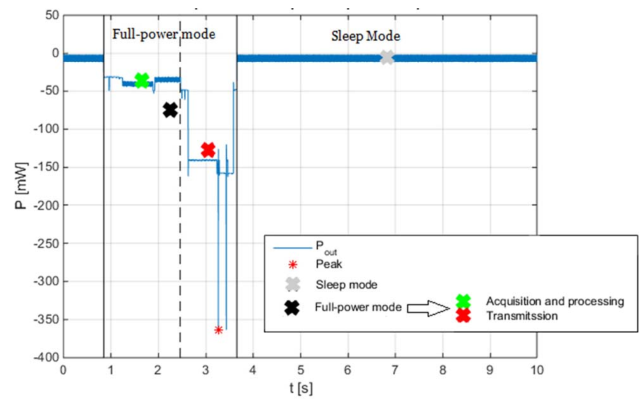


Fig. 10. NI laboratory test: battery power output during data acquisition, processing and transmission.

TABLE I

Consumptions of the Electronic Board in Full-Power Mode

Operation	Power consumption
Acquisition/processing	$35\ mW$
Data transmission	$126\ mW$
Peak power consumption	$360\ mW$
Total full-power mode	$65\ mW$
Total “wake-up” time (full-power mode duration)	$2.5\ s$
Total energy consumption during 1 full-power mode operation	$0.16\ J$

B. Mean Power Consumption in Sleep Mode

The mean energy consumption of the electronic board is studied by collecting the data transmitted wirelessly by the nodes on the Status of Charge of the battery. Setting a duty cycle of half an hour, the energy absorbed during full-power mode becomes more than one order of magnitude smaller with respect to the total energy requirements of the node, as suggested by equation (1). For this reason, it can be neglected and the consumption of the node in sleep mode can be considered equal to its total consumption.

$$P_{FP} = \frac{E_{FP}}{T_{duty}} \cong 0.1\ mW \tag{1}$$

where P_{FP} is the mean power consumption related to the full-power operation over a whole duty cycle period (T_{duty}) and E_{FP} is the energy required to perform a single operation (acquisition/elaboration/transmission).

In Fig. 11 the average daily consumption is shown in mAh over a testing period of about 6 months. According to such data, it is possible to conclude that the average consumption is not completely constant and mainly depends on the temperature (increasing when temperature increases) but, during the whole testing period, it remained below 20 mAh per day, with

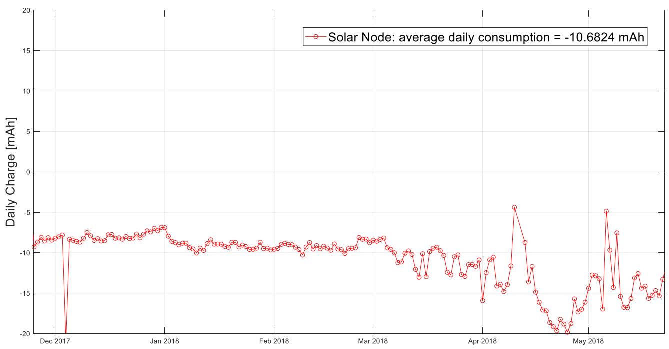


Fig. 11. Wireless laboratory tests: daily energy consumption.

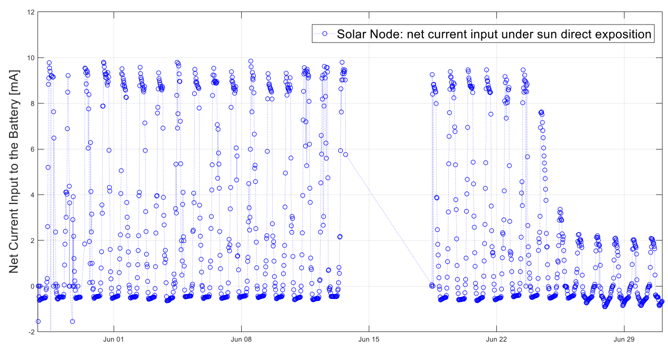


Fig. 12. Wireless laboratory tests: battery current input during direct sun exposition (1-month detail).

a mean value smaller than 11 mAh. The mean consumption of the node under standard working condition is estimated around 0.5 mA, that corresponds to about 2 mW, in terms of power.

Considering the so obtained consumption values, without any amount of energy provided by the solar panel, the battery only guarantees a working period from 4 up to 6 months.

C. Solar Panel Performances

The solar panel performances are studied exposing the node to direct sun until a complete recharge of the battery is reached. Fig. 12 shows the net current input to the node's battery during a testing period of about 1 month. When the maximum charge in the battery is reached, the accumulated charge remains constant with small cycles of charge and discharge related to the alternation of day and night. The energy used during night by the nodes to perform regular operations is easily recovered by the solar panel during the day, keeping the battery to its full charge level for the whole testing period. Performance of the solar node are summarized in Table II: the consumptions, during night, are in line with the previous estimations while the harvested current, during day, shows a saturation at 10 mA (corresponding to 40 mW in terms of power). This value is lower than the ideal performance of the solar panels; it is due to the maximum charging current that can be provided, through the LTC3331 IC, to the battery (as described in Chapter II).

Finally, from the balance between the energy consumed in the night and the energy recovered during the day, the estimated mean net current in input to the battery in ideal

TABLE II

SOLAR NODE HARVESTED POWER PERFORMANCES

CONDITION	NET CURRENT INTO THE BATTERY	NET POWER INTO THE BATTERY
During day	Up to 10 mA (saturation)	Up to 40 mW (saturation)
During night	-0.6 mA	-2.4 mW

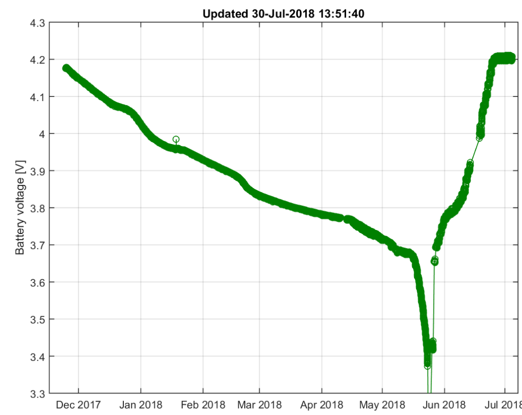


Fig. 13. Real-like laboratory tests: battery voltage.

conditions is 3.0 mA (corresponding to about 12 mW in terms of power).

These results lead to the conclusion that the harvesting system is able to introduce more energy than that consumed by a node with a duty cycle of 30 minutes. Starting from the energy consumption estimated with the previous tests, it is possible to evaluate that, with these energy performance, it would be possible to reach a duty cycle of 15 s, obtaining a complete balance between energy introduced and consumed.

D. Real-Like Working Condition Test

To characterize the overall performance of the battery and the solar panel in real like working conditions, the complete node has been tested over 7 months, before mounting it on a rail wagon. The wireless transmission protocol has been set to work with a duty cycle of half an hour, with a time acquisition window of 1s. The data on the state of charge of the battery are acquired and communicated by means of the wireless communication protocol to a PC. After the complete discharge of the battery, the node was exposed to direct sun radiation to be recharged.

In Fig. 13 and Fig. 14, the voltage and the accumulated charge of the battery are shown.

We can observe that the total time required for a complete discharge of the battery in absence of any external energy source is of 6 months, as expected from consumption test previously performed. The time required for a complete charge of the node in standard working (half an hour of duty cycle) is of 1 month, considering the day and night cycles. During the first part of the test, the mean consumption of the node was about 0.5 mA in terms of current (corresponding to about 2 mW in terms of power).

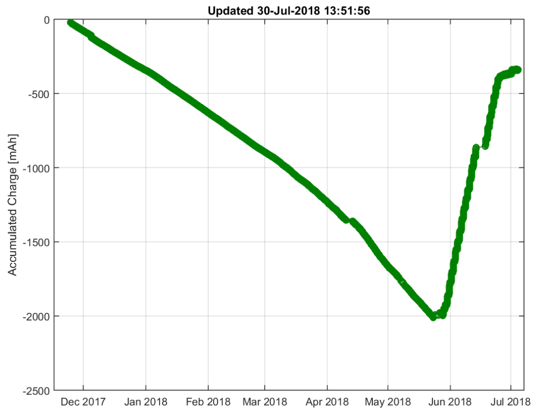


Fig. 14. Real-like laboratory test: accumulated charge.

Observing the second part of the test, when the node was exposed directly to sun, it was possible to assess the energy performance of the solar panel. As expected, Fig. 13 shows a positive trend of battery voltage asymptotic to its maximum value, indicating the correct working of the node.

VI. In-Line Tests

In the last part of the project, nodes were mounted on a Y25 freight wagon in commercial service and they were tested for a period of 10 months consecutively.

During the experimental campaign, performed in collaboration with Mercitalia, the freight wagon was equipped with a total of two Wireless Sensor Nodes and an on-board control unit, powered by a solar panel working in parallel with two batteries of 7Ah each. In Fig. 15 a picture of the experimental setup adopted during in-line tests is shown. One node was installed on the car body, near the control unit (Fig. 15-a) while the other was rigidly connected to axle-boxes (Fig. 15-c).

Each node transmits the data via wireless connection to the on-board control unit that uploads the information to a server by means of an internet connection, thanks to the GSM system installed in the control unit.

The same operation setting adopted for the laboratory tests was also used for the in-line test.

The summarized data sent by each node to the control unit include:

- mean and RMS value of the acceleration measured in the three directions;
- three spectrum line components of the vertical and longitudinal acceleration signals taken from the FFT analysis around the 1xRev frequency. (To correctly identify these components, the information about train speed, associated to the angular speed of the wheel, is transmitted from the on-board central control unit to each node)

Data coming from a 10 months period of acquisition are gathered in a 3×2 figure grid (Fig. 16). On the top left, the battery voltage is shown, in the center-left, the total amount of charge entering the battery and in the lower-left corner the current entering the battery. On the right column, the bus voltage on the top, the RMS of acceleration signal measured along the two axes (vertical and longitudinal) for the two nodes installed, and the train speed at the bottom can be found.

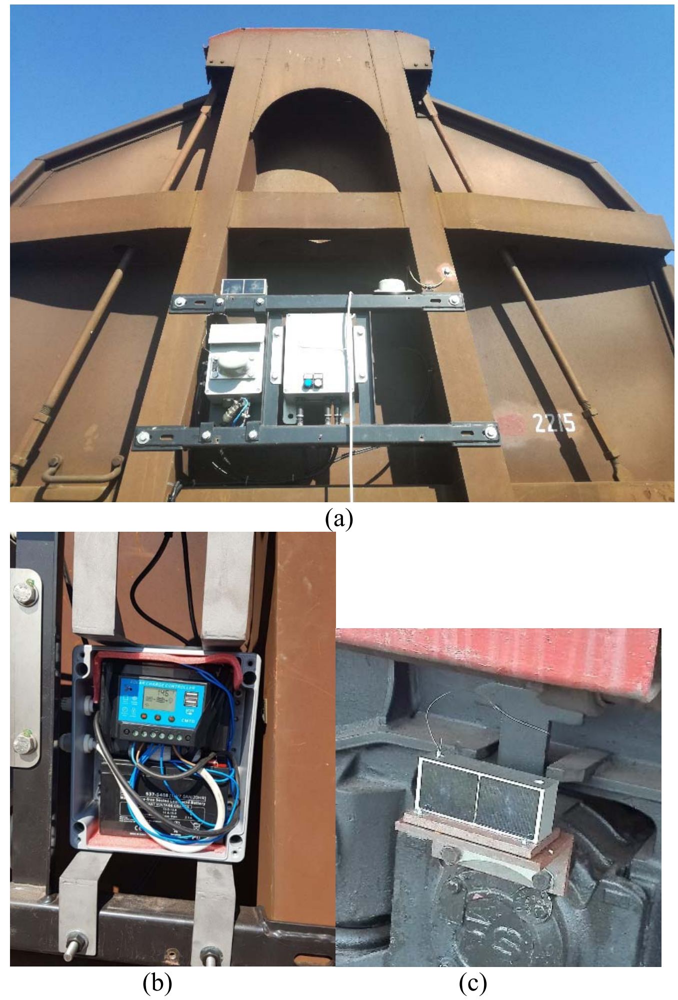


Fig. 15. In-line tests: Picture of the on-board central control unit installed at the tail of the wagon (a), detail of the battery pack and the controller that manages the powering of the central control unit (b) and the node on axle box.

The experimental campaign was organized into 2 phases. In the first phase, over four months between the beginning of December and the end of March, the train was kept stopped in the railway yard. During these months, the solar panel was exposed to direct sun and the battery was kept fully charged (as observed from the voltage that is kept constantly at the maximum value of 4.2 V). In the month of March there is a lack of data caused by the resetting of the central control unit setup and the change of the central solar panel. After this period of stop, the wagon started the normal service operations. From April to October a total amount of 26 trips of different length through Italy were monitored. Some lack of data occurred in August and September due to bad communication between the central-control unit and the server. Two periods are observed during which the battery has undergone a partial discharge due to the lack of direct sun exposition (cloudy days, or train not exposed to direct sunlight when parked in the railway yard). However, it emerged that some hours of sun exposition are enough to recover the energy lost during such periods.

Fig. 17 shows the GPS data gathered during the second part of the experimental campaign, highlighting the possibility of

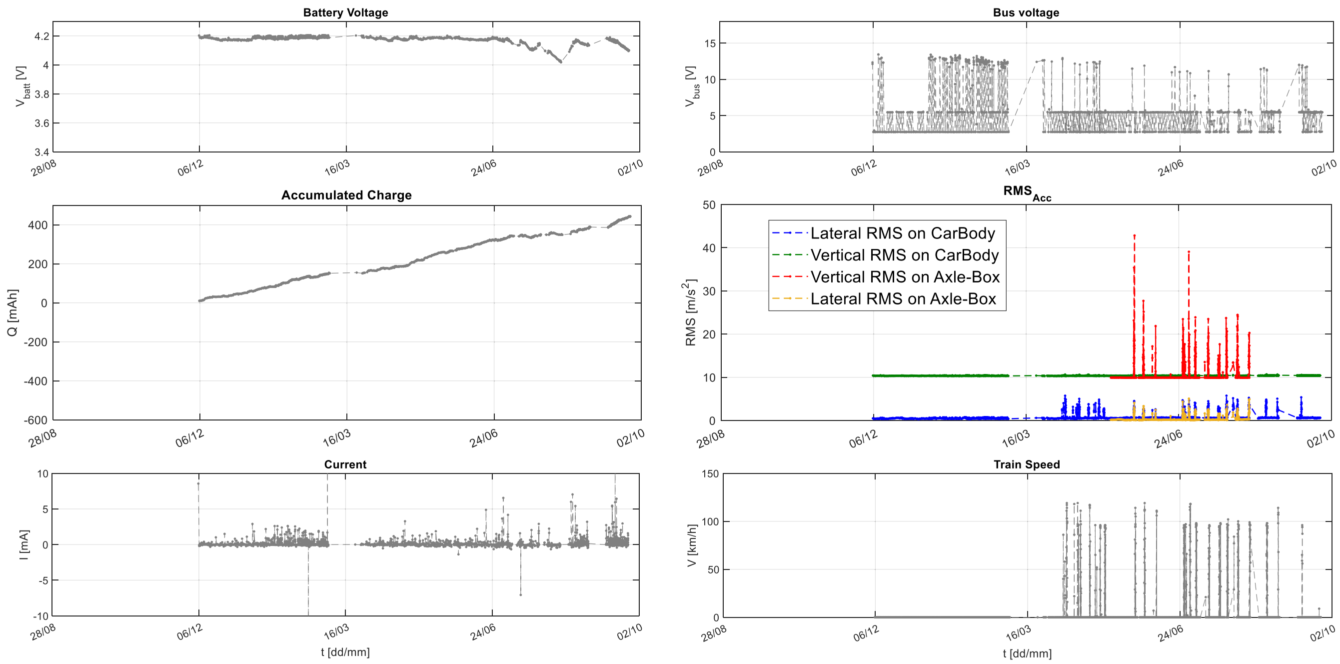


Fig. 16. In-line tests: summary of data obtained during experimental campaign. Battery voltage (a), Cumulated charge into the battery (b), Net input current to the battery (c), Bus voltage (d), Acceleration RMS along vertical and longitudinal direction (e), Train speed information (f).

Fig. 17. In-line tests: GPS location of the wagon moving across Italy during the tests.

performing a continuous monitoring of the wagon, but also of correlating the information about acceleration measurements to the actual wagon position.

A strong correlation between the vertical acceleration RMS and the speed train emerges, as expected, especially for the node installed on the axle-box.

VII. Conclusion

A Wireless Sensor Node for condition monitoring of freight trains powered by solar panel was designed and tested.

The Wireless Sensor Node was powered by means of a 1W solar panel that worked in parallel with a 2000 mAh rechargeable battery. The complete node was designed with the purpose of allowing monitoring operation on board of freight trains. The PCB was equipped with all the electronic components necessary to perform the correct management of data: a 3-axis digital accelerometer, a microprocessor, and a wireless transmission system. A particular focus was put onto the whole process that allows passing from raw data gathered in loco by means of sensors to a synthesis of data available on a server for elaboration, diagnostic and monitoring purposes.

The Wireless Sensor Node prototype was first assessed by means of laboratory tests (fatigue test and energy performances tests). The mechanical resistance of the node was assessed for a high number of cycles in worst-case conditions, reproducing the maximum vibration input undergone by the Wireless Sensor Node as measured on a previous experimental campaign on a real wagon, at its maximum speed.

By setting a duty cycle of 30 minutes, the solar panel adopted for powering the Wireless Sensor Node was shown to be able to guarantee long-life duration to the Wireless Sensor Node. It is able to provide the power required for all the operations of the electronic board and also an extra power to recharge the battery. The battery acts as a storage of energy and guarantees the correct working of the node, also in absence of sun radiation for a maximum period of 6 months. It was estimated that the designed node should be able to correctly operate, in conditions of energy balancing, with a duty cycle of only 15 seconds.

In the second part of the paper, the Wireless Sensor Network was tested by means of an experimental campaign on a Y25 freight wagon in commercial service. The Wireless Sensor Nodes described, thanks to the compactness obtained, can also be easily adapted to other freight wagon models. The communication protocol between the node and the onboard control unit was verified in this real case scenario. Data regarding the state of charge of the node battery, the RMS of vertical and lateral acceleration measured by the sensor node, and the position of the wagon were gathered every half an hour for the whole duration of the experimental campaign for a period of one year.

In conclusion, a wireless system for the monitoring of a freight wagon is assessed. This opens the opportunity to some interesting future works: from one side the possibility of implementing some specific algorithms for defect identification on board of the wagon, from the other side, collecting data from a huge number of sensors installed on different wagons, makes possible the development of new machine learning algorithms to verify the drive quality of the vehicle.

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