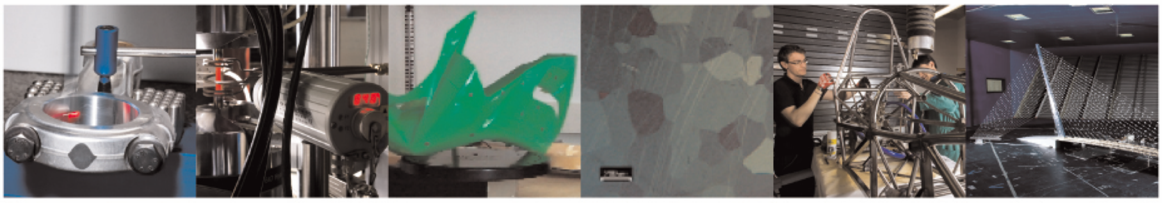

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Wireless Sensor Nodes for freight trains Condition Monitoring based on geo-localized vibration measurements

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Abstract

While rail freight transportation is gradually becoming a crucial asset in the context of decarbonization of the transport sector, new standards and requirements in this field aim at improving the safety and reliability of freight vehicles and the infrastructure. From this perspective, Condition Monitoring and Condition Based Maintenance are becoming essential tools to improve systems reliability through the use of in-service instrumented vehicles. On the contrary of high-speed applications, freight trains are actually not provided with any monitoring systems able to carry out this kind of analyses. In this context, an innovative hybrid monitoring system composed by wireless sensor nodes and a gateway was developed to be suitably mounted on a freight wagon. Sensor nodes, power supplied by solar energy, are able to carry out synthetic indices from vibration measurements, while the gateway acquires correlated GPS and odometry information. In order to take advantage of the acquired data, a software based on a geo-localization algorithm created for high-speed applications was developed in order to correlate vibration data to the railway line mileage. A field campaign allowed to test the system on a real freight wagon and to acquire many experimental data. Using the collected experimental data, in the paper is shown how the developed software can be used to perform diagnostic activities of the infrastructure. Moreover, it is demonstrated that relying on the only GPS information is sufficient to get enough accurate georeferenced data for freight trains applications. This paves the way to the future development of a completely wireless system able to perform condition monitoring of both the vehicle and the infrastructure minimizing the impact on the vehicle.

Keywords: Condition monitoring; wireless sensor nodes; train geo-localization; energy harvesting; vibration measurements.

1. Introduction

Condition Based Maintenance (CBM) and Condition Monitoring (CM) are becoming more and more important in the railway sector due to increasing traffic and more severe requirements on both the vehicle and the infrastructure safety and reliability [1-4]. Research works on this topic are widely present in literature, and it has been proved how installing sensors on-board train can be more effective and cheaper, with respect to infrastructure-based systems, for the monitoring of both vehicles and the infrastructure [5-16]. Through a fleet of instrumented vehicles, it is in fact possible to collect performance indices like acceleration RMS that can be used to perform trend analyses and therefore to understand if anomalies detected in data are related to a problem of train mechanical components or defects in the infrastructure [17-18]. This kind of CBM is nowadays almost a reality on high-speed trains where, thanks to this approach, it is possible to improve the safety of both the vehicle and the railway infrastructure [17,19,20]. The same cannot be said, instead, in the case of freight trains. The need of providing freight trains with smart and cost-effective monitoring system is becoming more and more important, since freight transport will represent in the near future a more sustainable alternative with respect to road transportation [21]. Although the focus of research works and industrial R&D is more on high-speed passenger trains ~~Although the safety of people is marginally involved in the freight transportation context~~, performing CM and CBM also in this field would allow to ensure less risk of accidents (especially derailments) connected to the degradation of both the vehicle components and the track [22]. There is therefore an evident necessity to equip freight trains with cheap and reliable sensors able to continuously acquire data for these purposes.

In this framework, sensor nodes mounted on passenger trains have the possibility to be power supplied by the on-board power generation systems. Freight trains, instead, ~~does~~ do not offer any power source on their wagons. In addition, cabling does not represent a feasible solution from practical and ~~the~~ economical point of view, ~~without neglecting~~ also because of the necessity to have independent wagons due to train reassembly after every travel. Hence, there is an increasing need of a self-powered wireless monitoring systems for freight trains characterized by low consumption and high reliability, useful to evaluate possible degraded dynamic behaviours related to the vehicle or to the infrastructure [21]. A solution of wireless monitoring device for the monitoring of intermodal freight wagons is proposed in [23]. The developed hybrid monitoring system can be used to carry out measurements on the braking and axle box subsystems. The main issue is represented by the need of a power supply to recharge batteries. In recent years, research studies aiming at identifying the best energy source to be harvested on a train were carried out. A comparison between the performance of a piezoelectric harvester, a photovoltaic panel and a micro wind turbine was performed in [24] in order to understand which of the tested solutions was the most suitable to power supply wireless sensor nodes. Solar energy was found as the most suitable and affordable energy source to be harvested in this scenario. In the subsequent developments [25], several tests were carried out on the realized prototypes showing the efficiency of the solution. A 10-months field test on a freight wagon allowed to acquire useful data regarding the performance of the sensor nodes and to gather vibration measurements. However, the power consumption of the device was not suitable to acquire data with continuity (the 30 minutes duty cycle cannot be considered suitable for an operational use). In addition, vibration data were not correlated with the railway track, making them unfit for diagnostics purposes. In fact, the capability to associate diagnostic indicators to the to the train positioning along the railway line is of paramount importance for condition monitoring of both the rolling stock and the infrastructure [26]. The solution based on photovoltaic panels as energy harvester was also adopted successfully in another field campaign on a freight train with the aim of monitoring pressure variations inside the braking system [27].

For these reasons, a new smart and low consumption system was developed with the aim to perform condition monitoring by acquiring acceleration synthetic data georeferenced through GPS and odometry information. The developed solution, composed ~~by~~ of a certain number of wireless sensor nodes and a gateway, represents a sort of hybrid system. The “hybrid” denomination comes from the fact that an axle-box generator is mounted on the vehicle to take advantage of this component for the power generation necessary for the gateway power supply and for the odometry measurement. A cable connection is therefore present between the gateway and the axle box. Scope of this work is also to show how it is possible to perform condition monitoring on freight trains through a system characterized by lower performances with respect to the ones mounted on commercial trains. The future perspective is the development of a full wireless architecture, based uniquely on GPS information, which is completely independent from the rail vehicle, also from the power supply point of view. The paper is organized as follows: section 2 describes the development of the innovative Wireless Sensor Nodes created for this project, while section 3 illustrates the experimental set-up adopted for the field campaign carried out instrumenting a T3000e freight wagon made available by Mercitalia Intermodal. Section 4 is devoted to the description of the geo-localization software, based on the algorithm developed in [26]. In section 5 the main experimental results are proposed, with the aim of validating the system developed (both the hardware and software parts) and of showing its usefulness for diagnostic purposes. In the end, some conclusions and future perspectives are reported in section 6.

2. Sensor nodes description

The sensor nodes designed for this project are based on the ones described in [~~27~~28,29]. They are basically composed ~~by~~ of an ad-hoc developed electronic board and a Lithium Polymer (Li-Po) battery which are installed into a 3D printed plastic body. On the top of the enclosure, a mini photovoltaic panel is placed to recharge the battery when it is hit by the sunlight. The main components present on the electronic board are a microcontroller, a triaxial Micro Electro-Mechanical MEMS accelerometer (ADXL 345 by Analog Devices), a Bluetooth Low Energy (BLE) transceiver and an integrated circuit which performs the on-board power management. The main technical features of the mounted MEMS accelerometer are summed up in Table 1. The measurement range adopted for the field test corresponds to the highest available (i.e. ±16g) to be on the safe side on measurement activities, avoiding possible accelerometer saturation. This choice does not translate into a lower accuracy since for this specific accelerometer the amplitude resolution remains constant varying the measurement range. The choice of BLE for wireless communication is motivated by the good communication range, the high maximum data rate and the low consumption guaranteed by the implementation of this protocol [~~28~~30].

ADXL 345 - Main technical features	
Measurement Range	±2g, ±4g, ±8g, ±16g
Sensitivity	256 LSB/g
Noise	1.1 LSB rms
Output Data Rate	3200 Hz

Table 1 – MEMS accelerometer main features

With respect to the architecture described in [~~27~~28,29], sensor nodes developed for the freight train application share the same hardware except from the implementation of a different Bluetooth transceiver, namely the Fanstel BT840e instead of Fanstel BT840F. This choice allows to provide nodes with an external antenna useful to guarantee a good communication with the gateway also in this complex environment, characterized by the presence of a huge iron body and many shielding. Regarding the firmware part, they are instead totally different with respect to the ones described in [~~27~~28,29]. The state machine is here characterized by the presence of three main states: “Wake”, “Run” and “Sleep”. In the “Wake” state the sensor node sends to the gateway a Wake message every 30 s. If the gateway is active, it answers to the sensor node with a message containing the Timespan information, in order to synchronize each sensor node acquisition. When the node receives this synchronization message, it goes in the “Run” state and acceleration data are acquired continuously with a 200 Hz sampling frequency. The choice of the sampling frequency has little influence on the sensor node autonomy because the highest power consumption is reached in the data transmission stage. Since computations are performed on-board sensor nodes and synthetic indices are transmitted to the gateway, the amount of data to be sent away is independent on the selected sampling frequency.

In particular, the acceleration RMS is calculated on-board by computing the Fast Fourier Transform (FFT) over a time window of approximately 1.28 s (256 samples) on the three frequency bands reported in Table 2 for each axis. The frequency bands have been defined to detect specific conditions related to the vehicle dynamics and to the infrastructure degradation. As an example, Band 1 (1-10 Hz) in the case of lateral accelerations can be used to identify the occurrence of bogie hunting instability. The same Band 1 in case of vertical accelerations is useful to monitor the vertical track profile. In particular, RMS acceleration belonging to this frequency range may provide useful information with respect to longitudinal level defects in the D1 range (wavelength in between 3-25 m) considering the cruising speed of 100 km/h typical of a freight vehicle [31]. Higher frequency bands have been set up with the aim of investigating possible effects related to punctual defects of the infrastructure. The application of this approach will be illustrated in the analysis of the collected experimental data, shown in the last section of this work. In addition to these data, sensor nodes acquire, over the same time window, also the maximum acceleration peak measured on each axis and its position in time. Under certain conditions (which will be explained in the next section), the gateway can send a message to the sensor node to put it in the "Sleep" state. The power consumption is hugely reduced in this condition since the microcontroller is put in low power mode and the BLE transceiver is in reset state.

Frequency Band 1	Frequency Band 2	Frequency Band 3
1-10 Hz	15-30 Hz	45-60 Hz

Table 2 – Frequency bands characterizing RMS computation

The realized prototypes dimensions are approximately 91x70x38 mm, while the weight is about 240 g. Thus, the designed sensor nodes are characterized by compact dimensions and low weight which assure fast and easy installation in complex structure, such as the frame and bogies of a freight wagon.

3. Experimental set-up

The instrumented freight wagon is represented by a three-bogie T3000e wagon which is much used in the intermodal transportation field. During the 3-months field test, the convoy in which the instrumented wagon was inserted travelled mostly on the Verona – Rotterdam railway track. One of the two semi-wagons was instrumented with the developed "hybrid" monitoring system, composed ~~by~~ of the wireless sensor nodes, the gateway and the axle box generator (comprehensive of odometer). In addition, for this experimentation it was chosen to make use of one wired accelerometer to realize a benchmark with measurements acquired by wireless nodes. With the aim of being a reference for the measurements carried out by the wireless sensor nodes, the wired accelerometer has been selected with features (reported in Table 3) similar to the ones of wireless nodes. An anti-aliasing filter has been implemented to guarantee a reliable measurement in the frequency range of interest. A scheme of the hybrid system is proposed in Figure 1.

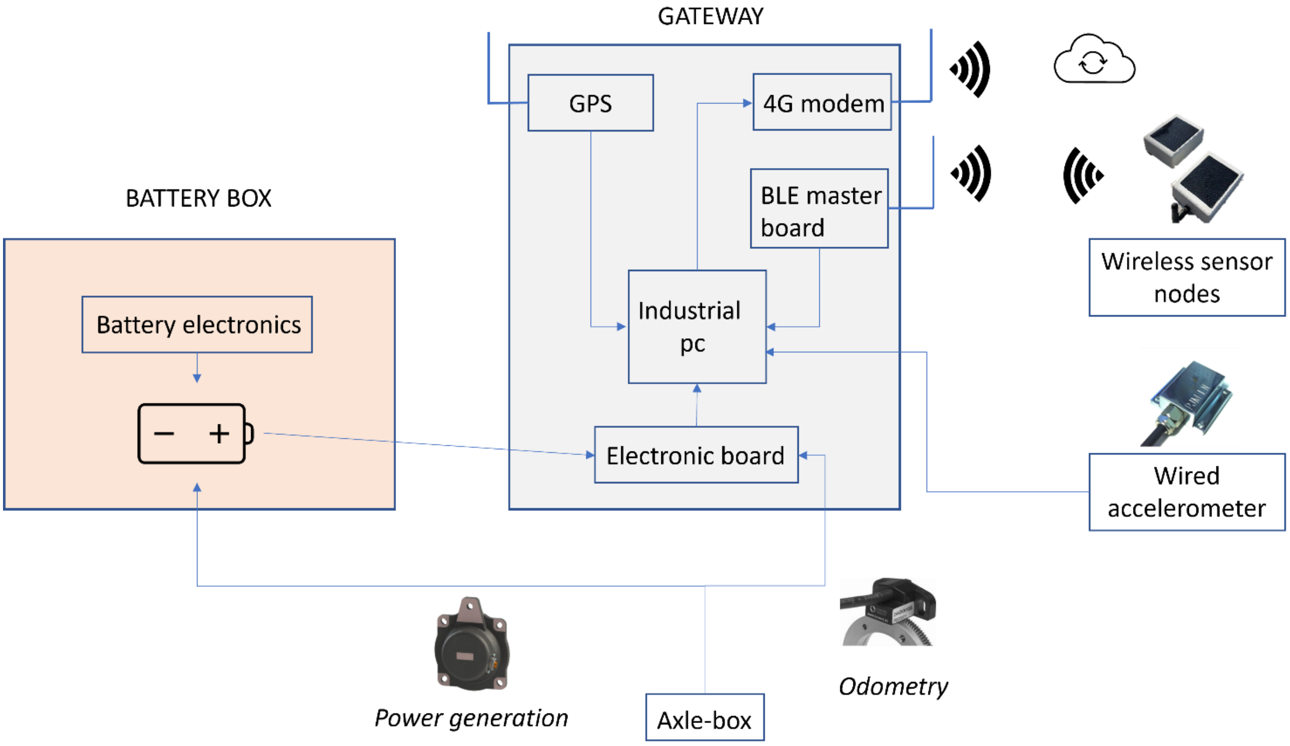

Figure 1 - Scheme of the developed hybrid monitoring system

~~The main features of the wired accelerometer are listed in Table 3.~~

Wired accelerometer	
Measurement Range	±5g
Sampling Frequency	500 Hz
Filter	Butterworth low pass 80 Hz, 4th order

Table 3 – Wired accelerometer main features

Two wireless sensor nodes were placed on the central bogie (‘CB’ and ‘BD’ sensor nodes) while the remaining four sensors (‘B8’, ‘2E’, ‘4A’ and ‘C8’) were placed in significant points of the wagon frame (Figure 2).

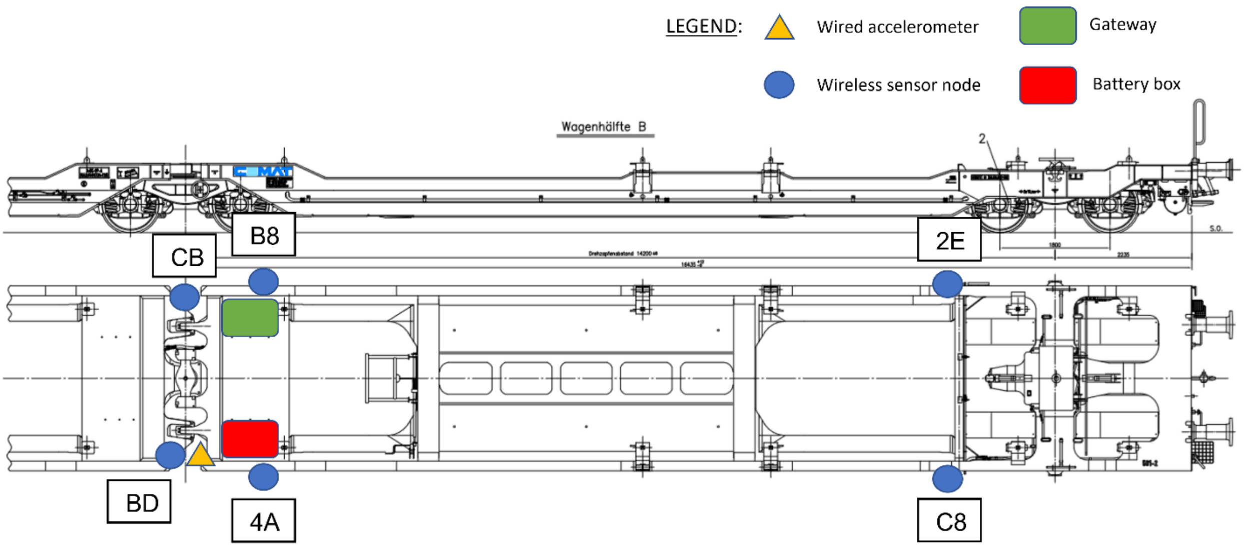

Figure 2 - Experimental set-up positioning on the Mercitalia Intermodal T3000e freight wagon

Sensor nodes were fixed through the chassis by means of a suitable bicomponent epoxy adhesive. A wireless sensor node and the reference wired accelerometer positioned on the bogie are visible in Figure 3a. A node installed on the frame is instead visible in Figure 3b.

(a)

(b)

Figure 3- Sensor nodes mounted on the Mercitalia Intermodal T3000e wagon. a) Wireless sensor node and reference wired accelerometer placed on the bogie. b) Wireless sensor node mounted on the frame.

Sensor nodes communicate wirelessly with the gateway positioned on the wagon frame. The gateway is power supplied by a suitable battery which is recharged, when the train is in movement, by the axle-box generator. The gateway main function is to collect data from the sensor nodes, post process them and send synthetic information to the Cloud. The gateway is essentially composed by an industrial pc, a 4G modem, a BLE master board, a GPS receiver and an electronic board used to manage the energy consumption of the system. The master board is used to gather data from the sensor nodes and transmit them to the pc through serial connection. A Matlab script, running on the industrial pc, manages the acquisition procedure. The role of the electronic board, developed ad hoc for this application, is instead to manage the duty cycle of the entire system according to a power saving logic. On the basis of this logic, the pc is turned on when the pulse counter assumes an increasing value for 10 consecutive seconds, which identifies the condition of the moving train. Analogously, when the train is no more running, which translates in the pulse counter value standing still for more than 60 seconds, the pc is turned off in order to save energy. Moreover, this board is used to communicate to the pc diagnostic data regarding the battery status.

Every time the train begins moving, the acquisition procedure starts automatically, and each data packet acquired from the sensor nodes is associated locally with the odometry and GPS information.

The gateway, in addition, is used to acquire the GPS information from the receiver installed on the frame and the odometry information coming from the pulse counter in the axle-box. The GPS and odometry data are acquired both with 1 Hz sampling frequency. To carry out data geo-localization, a suitable algorithm was developed and ~~made~~ run on~~-board~~ the gateway.

4. Geo-localization algorithm

In order to geo-reference data acquired by wireless sensor nodes, taking advantage of the odometry and GPS information available, a geo-localization algorithm was developed~~. The basis for this software is~~ based on the one ~~algorithm~~ developed for high-speed trains described in [26]. The parameters adopted for the acquisition phase in the high-speed context were a refresh time equal to 250 ms for GPS coordinates and 100 ms for the odometry signal. Anyway, due to the lower speed of a freight train, a lower sampling frequency of 1 Hz could be admitted for both the GPS and odometry signals.

Overall, the main advantage the algorithm provides is to carry out a reliable geo-localization of the instrumented freight wagon in order to link the recorded acceleration data to the exact position along the railway line where they were acquired. In doing so, the repeatability of the signals can be guaranteed, and gathered data can be superimposed and compared for trend analysis.

Wireless sensor nodes are able to transmit to the gateway synthetic indices (such as acceleration RMS), allowing to save time and computational effort in the post-processing phase. The main target of the developed algorithm is to obtain geo-referenced diagnostic indicators along the lines under analysis by means of the assignment of a corresponding line mileage. The latter represents the univocal positioning reference for each line, which is constituted by a series of milestones identifying a progressive location along the track, starting from a conventional baseline. This method is adopted by the railway infrastructure manager to drive maintenance interventions. In doing so, each gathered signal can be uniquely related to the correspondent line mileage, referred as PK.

~~The assessment of the train location along the track can be performed from the evaluation of the starting position of the vehicle and the progressive distance covered during its run. Taking advantage of the odometer, it is possible to compute the travelled space knowing the wheel's diameter, so as to obtain the train positioning along the line~~ A well-known problem related to the mere use of odometry signal for train positioning is related to ~~But actually,~~ some inaccuracies which may arise in the estimation, mainly due to the occurrence of drifts phenomena for which the distance travelled by the train is higher (in case of wheel lock during braking) or smaller (in case of slipping during accelerations) than the space deduced by the odometry, as it will be better explained in the following. Alternatively, it is possible to assess the train positioning using the GPS information. However, the collected GPS coordinates can in some circumstances be affected by low precision related to temporary lack of signal, as a consequence of the passage through a tunnel or a region where the signal reception is difficult, resulting in a poor estimation of the vehicle positioning.

To solve these issues, the developed algorithm takes advantage of both odometry and GPS information. The first operation performed is the comparison of the acquired GPS coordinates with a "digital map" of the railway line, with the aim of improving the geo-localization reliability. This "digital map" consists in a set of coordinates (latitude and longitude) mapped about every kilometre along the track and associated to the corresponding milestone. For this project, the digital maps of both the track sections Milano-Verona and Verona-Brennero travelled by the freight wagon were available. Through a geometrical process, named as map-matching, in the algorithm each acquired point is projected on the correspondent segment of the digital map [26], so that the train positioning along the line can be identified not only in terms of GPS coordinates, but also according to the milestone position. Looking at the Figure 4a, green points represent the GPS acquisitions (blue points) projected on the digital map of the railway line (continuous red line). The line mileage corresponding to the projected points is then computed through the lever rule. At the end of the process, the initial GPS positions are substituted by a new set of coordinates which represents a better estimation of the train positioning along the line mileage.

After the application of the map-matching procedure to the GPS information collected by the train, the second step performed in the algorithm is to improve the reliability of the line mileage even in case of missing GPS signal, reducing meanwhile as much as possible the occurrence of outliers related to the intrinsic GPS device accuracy. This is carried out introducing an analytical relation between the odometrical data and the results obtained from the map-matching procedure. In particular, the implemented relation considers the odometry values as input and provides as output the corresponding value of line mileage PK according to (1).

$$PK = m\,Od + q \tag{1}$$

where m and q coefficients are computed with the robust-fit function (C and e parameters respectively in Figure 4b), Od are the odometry values acquired and PK is the estimated line mileage (expressed in km in Figure 4b).

The angular coefficient m in (1) represents a key parameter to take into account possible drifts in the odometry for the line mileage estimation. If no drifts occur, a theoretically perfect coincidence between PK and odometry is expected, situation that would lead to m=1. Conversely, the presence of sections where sliding or slippage may occur, can influence this proportionality factor, leading to a value smaller than 1 in case the wheels are slipping (acceleration phases) and greater than 1 in case wheels are sliding (braking phases).

~~The~~ A robust-fit function is ~~therefore~~ then implemented ~~in order~~ to reduce the influence of outliers on the evaluation of m and q coefficients, by means of an iteratively reweighted least square algorithm [26]. ~~The weights are computed, for each iteration, by applying a proper weighting function to the residuals resulting from the previous iteration. Through this operation, the algorithm carries out lower weights for data which are characterized by high residuals, due to their relevant distance from the fitting line with respect to the trend of neighbours. In this way, the final fitting line results less sensitive to outliers if compared with a traditional least-square regression.~~

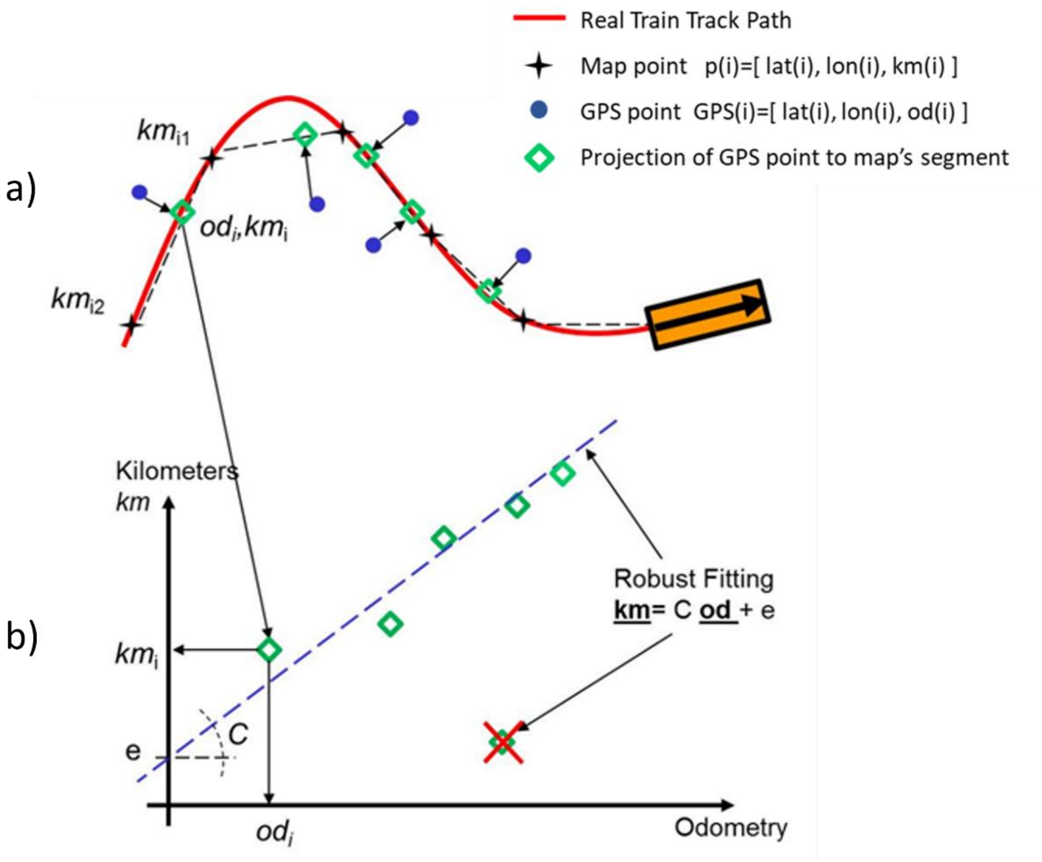

Figure 4 – Representation of the use of a) the map-matching procedure and b) of the robust-fit function

An example of the application of the developed geo-localization algorithm to a train run on the Milano-Verona track section is shown in Figure 5. In the graph on the left, the output of the map-matching procedure, which realigns the acquired GPS coordinates on the railway line "digital map", is represented. The error in terms of distance between the acquired GPS points and their projections on the map is shown in bottom right position, while on the upper right of the figure the outcome of the robust fit procedure is represented. The GPS errors can be due to both acquisition problems of the device or mistakes in the digital map of the railway line, in particular when a multi-track environment is present in the considered section.

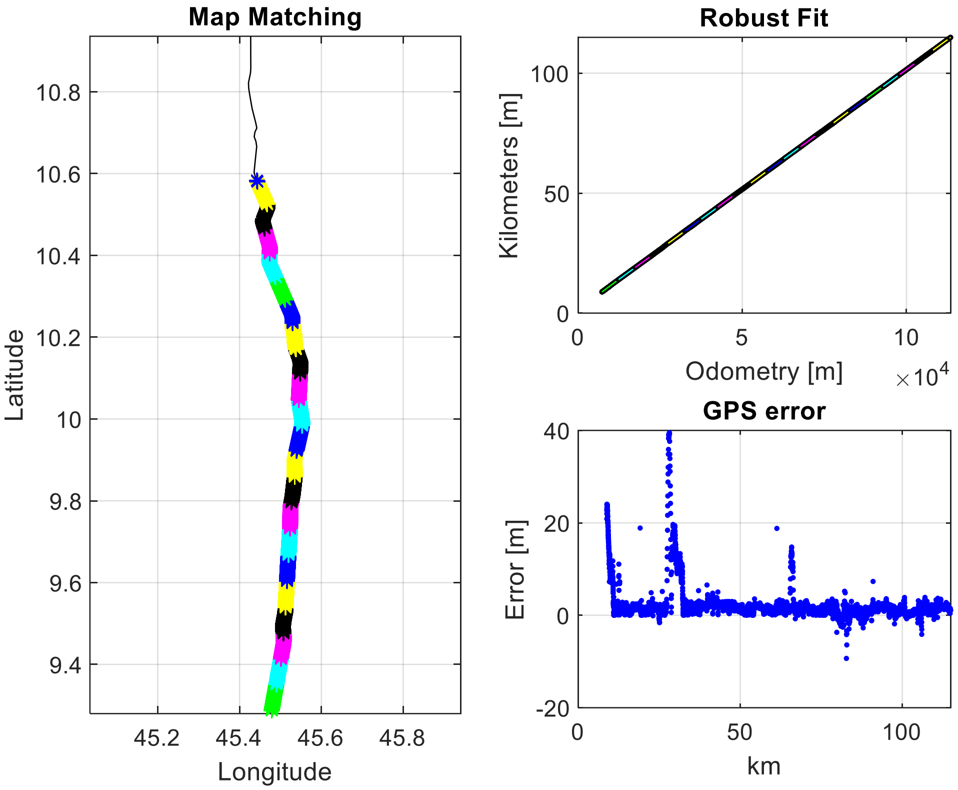

Figure 5 – Main outputs of the developed geo-localization algorithm

As in the case of high-speed application [26], also in the case of freight trains, odometry and GPS information processed as in Figure 5 allow to get a reliable vehicle geo-localization. The acquired acceleration data, processed in terms of RMS as explained in the following sections, can then be properly geo-localized based on the described algorithm. In Figure 6 a comparison between the results obtained through the use of the complete algorithm (i.e. relying on the robust-fit procedure, GPS information plus odometry, yellow line) and the algorithm based uniquely on map-matching (GPS data only, red line) is proposed. Acceleration RMS values are evaluated over a 100 m long spatial window, comparing the results of the PK estimation obtained through the geo-localization algorithm.

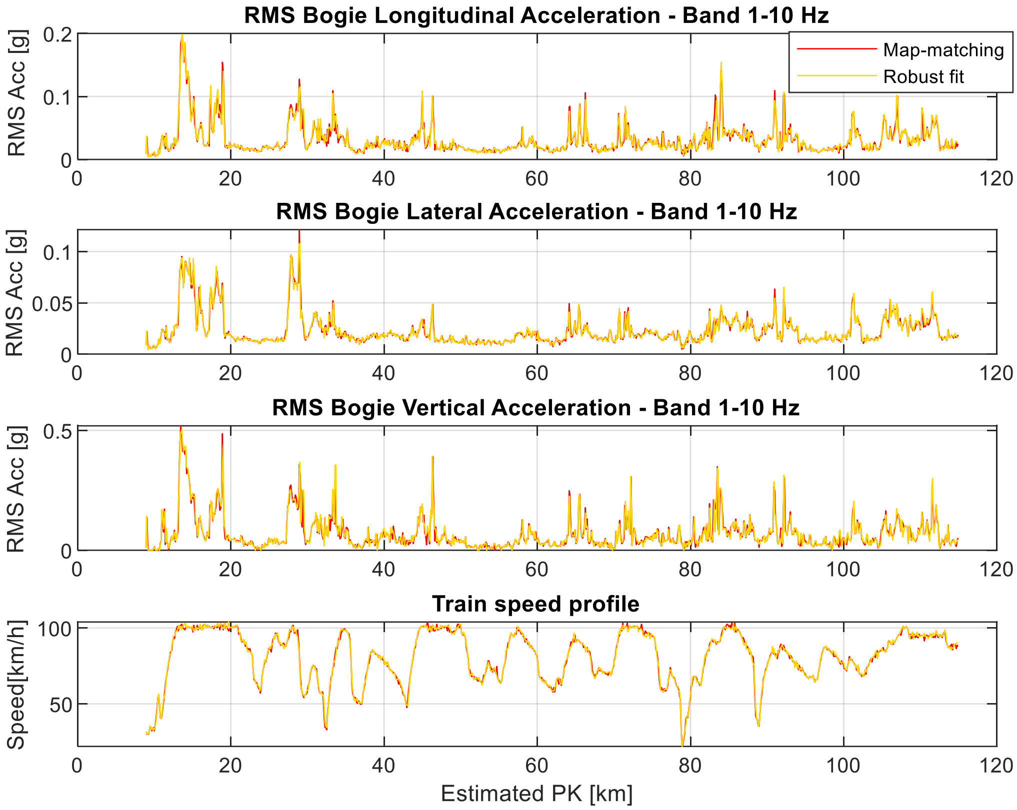

Figure 6 – Comparison between results geo-localized through map-matching and map-matching+robust fit techniques

As can be noted, the results obtained are in this case very similar for both the algorithms. The robust fit procedure seems not to add a significant accuracy with respect to map-matching one, mainly ~~because~~ due to the absence of relevant outliers and to the fact that the adopted acquisition parameters are not so demanding as the ones chosen for high-speed applications. Therefore, for freight application in the absence of relevant outliers, taking advantage of the GPS information only could be sufficient to carry out the geo-localization task. This will be fundamental in a future development of the system, since it will allow to design a full wireless monitoring system by implementing a GPS module on each sensor node. In the following analyses, data are processed through the use of the algorithm based on the map-matching procedure only, since it was proved that the accuracy reached is satisfactory for the considered framework.

5. Experimental results

5.1 Accelerometer measurements comparison

A good amount of experimental data was acquired during the field campaign. However, it has to be pointed out that wireless sensor nodes were not able to perform acquisitions continuously during the field test, since freight trains very often travel at night. This fact, together with the winter season, clearly puts a cap on the efficiency of the energy harvesting system implemented in sensor nodes to recharge batteries. Anyway, considering all the travels performed, sensor nodes were on average active for approximately the 65% ~~more than 60%~~ of the travelling hours. This result is any case satisfactory ~~can be viewed still as a good result~~, considering how unfavorable were the environmental conditions for the good functioning of photovoltaic panels. The amount of collected experimental data made it possible to validate the use of geo-localization algorithm in this context (as it will be shown in the following), which represented the main goal of this work. Clearly, in order to adopt the designed monitoring system for detection of derailments or vehicle faults a more robust source of energy, able to power supply sensor nodes with continuity in time, has to be found. Concerning infrastructure monitoring, this acquisition rate might still be useful for this purpose considering the instrumentation of the entire fleet of vehicles. When more trains of the fleet are instrumented, several acquisitions would be carried out daily on the same track sections, allowing to perform diagnostic activities of the railway track.

~~On the contrary~~ On the other hand, the wired reference accelerometer acquisitions were clearly not affected by these issues. Acceleration data collected by the wired accelerometer were then used to assess the validity of data acquired by the wireless sensor nodes. The comparison is carried out on data acquired by the two sensors positioned on the bogie (shown in Figure 1) considering a travel performed by the train on the Verona-Milano track section. It has to be pointed out that acceleration data coming from the wired accelerometer were acquired in the form of time-histories. In order to employ them for the comparison, these data have been processed in the same way as wireless nodes carry out the acquisition. In particular, the FFT is applied to raw data on 1.28 s long time windows, and then the RMS is computed, taking advantage of Parseval's theorem, over the same frequency bands reported in Table 2 according to (2).

$$RMS = \sqrt{2 \sum_{f=0}^{f=SR/2} |X(f)|^2} \tag{2}$$

where SR is the sample rate, while $|X(f)|$ represents the modulus of the complex components of the FFT at each spectral line.

In this comparison, data related the first frequency band (1-10 Hz) for each axis are taken into account. Data are then processed with the geo-localization algorithm in order to be plotted on the estimated line mileage PK. After this process, RMS acceleration values are condensed into synthetic indicators by performing another RMS in the space domain, considering windows 100 meters long. The obtained results are visible in Figure 7.

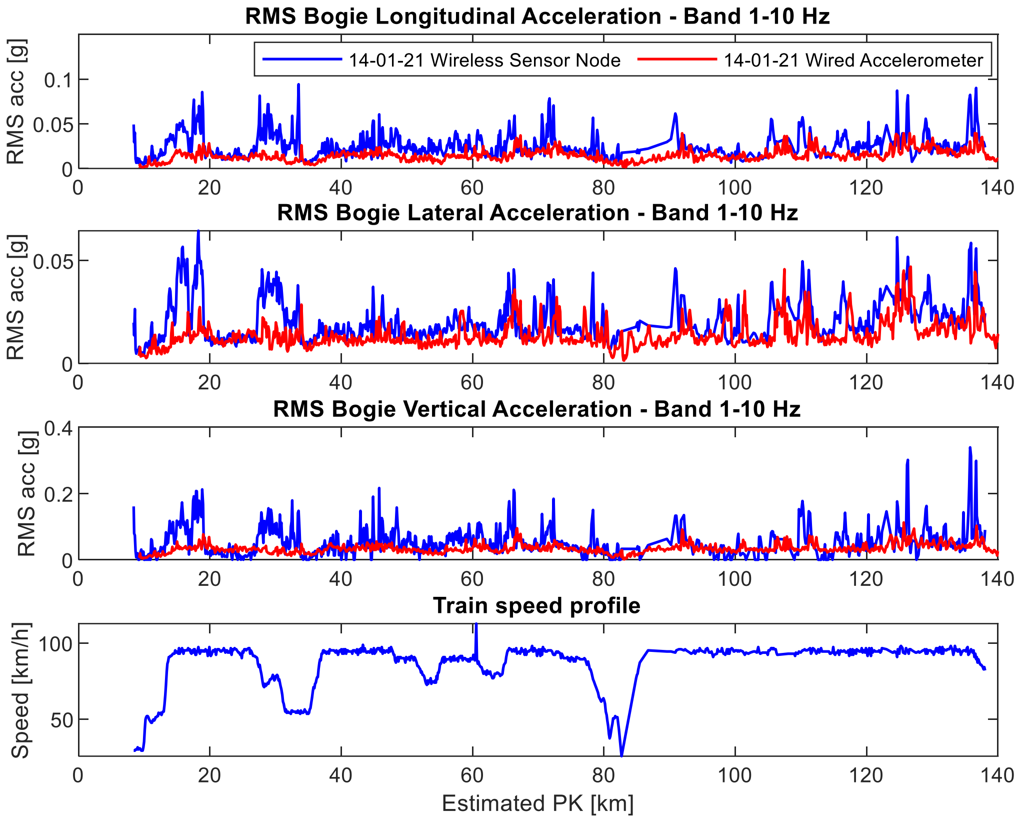

Figure 7 – Comparison between acceleration data coming from the wireless node and the reference accelerometer

A strong coherence between data acquired by the wireless sensor node and those collected by the wired accelerometer can be appreciated in Figure 7. However, some differences can be observed in terms of RMS acceleration maximum values. This can be related to the different filtering options implemented in the two devices. In addition, as already explained, the sensor node MEMS accelerometer is mounted on the developed PCB which is then screwed to the enclosure body. This can enhance the amplitude of vibration measured by the MEMS accelerometer (i.e when one or more natural frequencies of the PCB board lays in the frequency excitation range). Anyway, from the performed analyses it clearly comes out that the developed algorithm works efficiently since measurements repeatability is assured. In conclusion, the agreement is satisfactory in all the three directions of this comparison, allowing to assess the validity of the acceleration data gathered by means of wireless sensor nodes during the campaign and to proceed with further analyses.

5.2 Algorithm assessment using data repeatability

The efficiency of the developed geo-localization algorithm is evaluated by superimposing data acquired from the wireless sensor node positioned on the bogie during different travels on the same track section, namely the Verona-Brennero one (Figure 8). The vertical acceleration measured on the bogie is taken as the frame of reference since it represents the most significant parameter for this kind of analysis [~~29~~32].

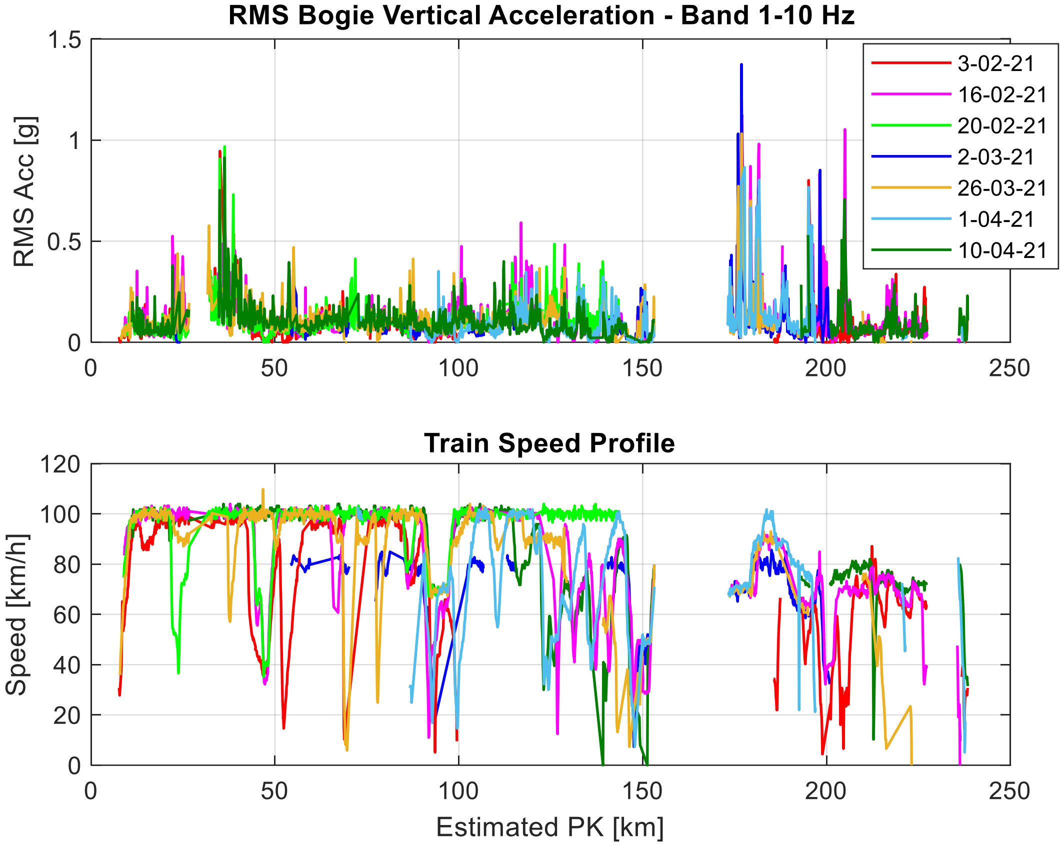

Figure 8 – Superimposition of georeferenced vertical acceleration data of several travels on the Verona – Brennero railway section

The missing data sections are caused by sensors run out of battery and by GPS signal losses due to the presence of very long tunnels. Anyway, a good superimposition of RMS acceleration peaks can be observed. Focusing only on some travels, it is possible to observe the relationship between RMS acceleration values and the train speed (Figure 9). Clearly lower train speeds correspond to lower acceleration values (black rectangle). Anyway, the measurement repeatability is ensured also in presence of very different speed trends, as can be observed looking at the blue rectangle.

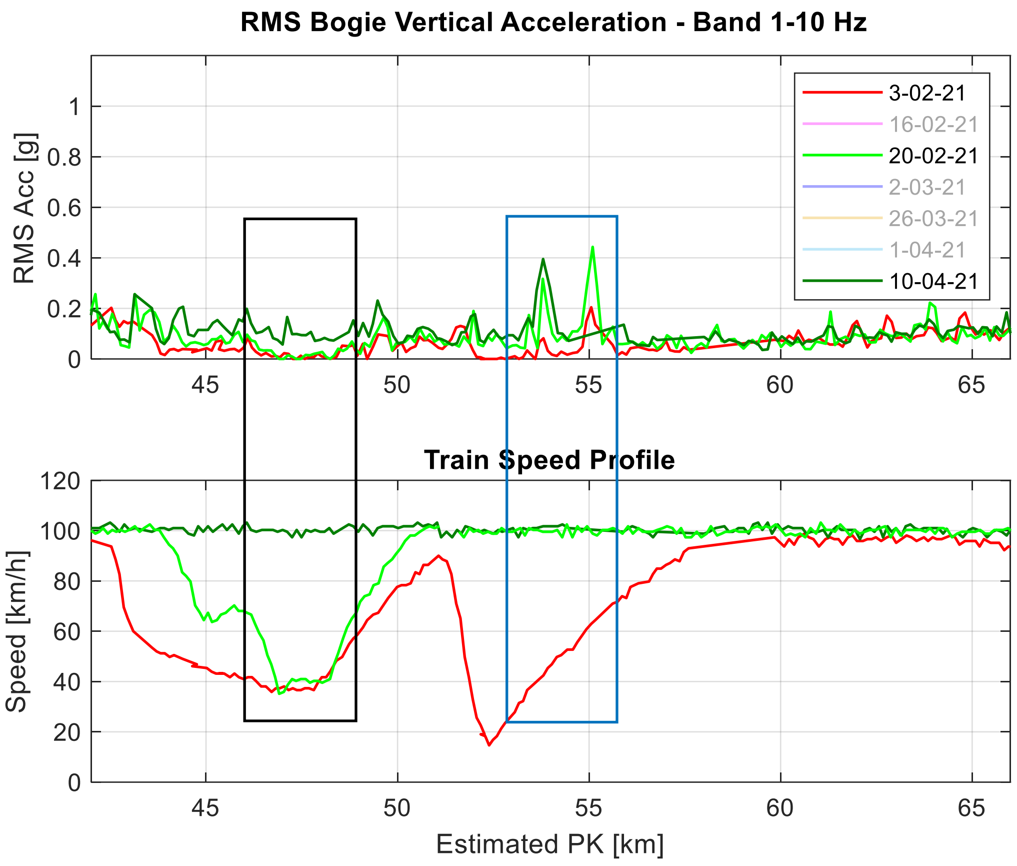

Figure 9 – Focus on a specific railway section inside the comparison of data with very different speed trends

The strong measurements repeatability is then highlighted in Figure 10, where a focus on a specific portion of the track (around the 180th kilometer) is proposed. Some travels were hidden since no data were available for this specific section. Travels with very similar speeds present RMS peaks nearly superimposed both in terms of magnitude and position on the railway line.

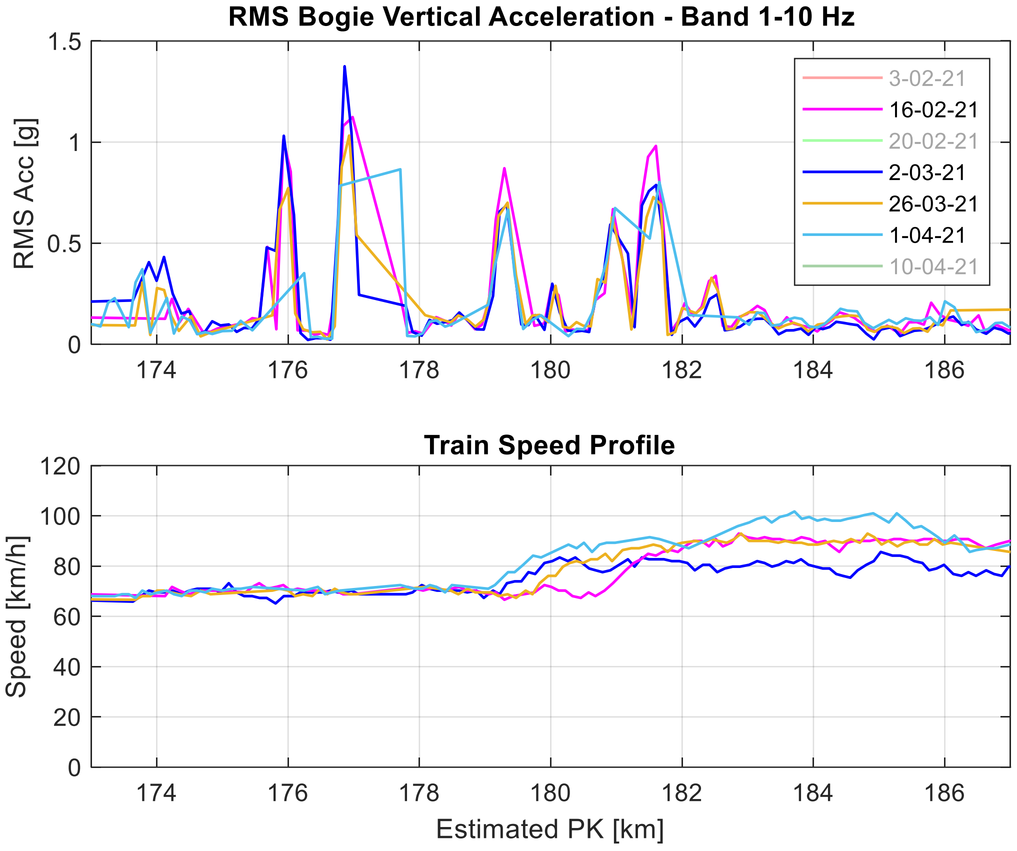

Figure 10 – Focus on a portion of the railway track where the repeatability is highlighted

Lastly, since the acceleration measurements carried out by wireless sensor nodes are available on the three axes, the repeatability was assessed also for lateral acceleration. Also in this case, a good agreement between data acquired during the different travels can be observed (Figure 11).

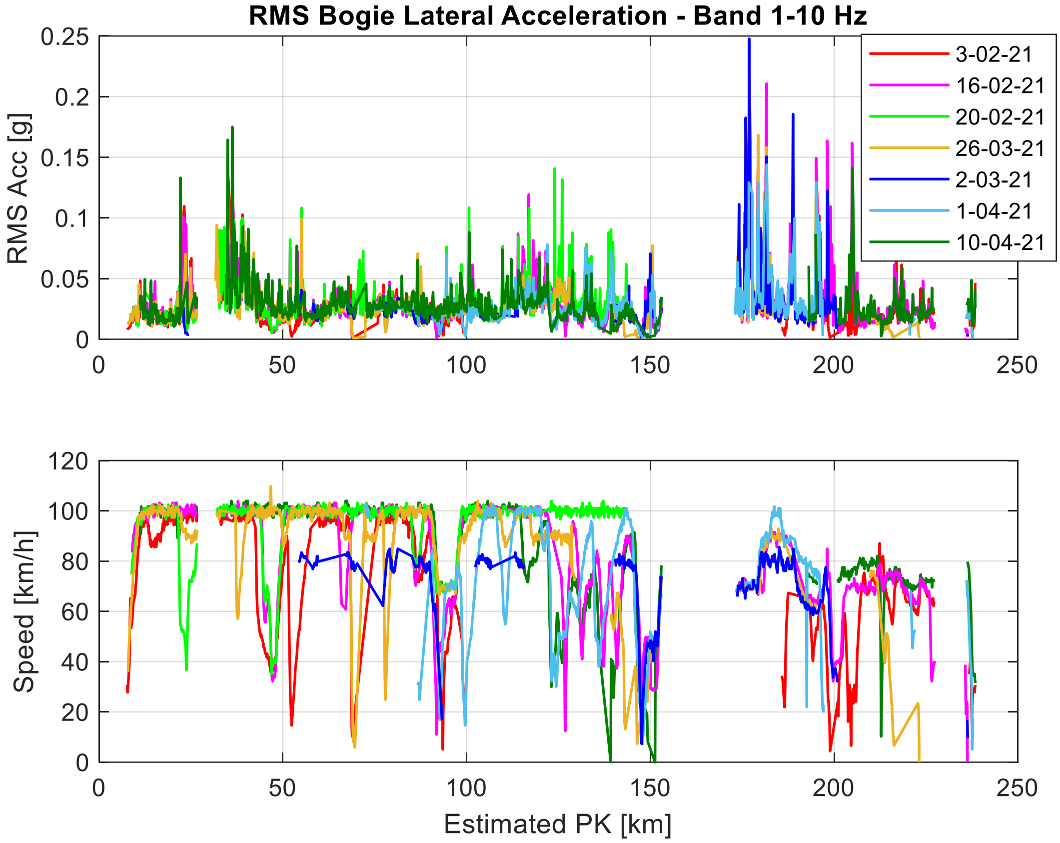

Figure 11 - Superimposition of georeferenced lateral acceleration data of several travels on the Verona – Brennero railway section

This is a considerable result since it could allow to perform analysis on the train dynamic behaviour in curves, provided that this kind of information is available in the railway digital map. In conclusion, the good data repeatability allows to confirm the use of this kind of geo-localization algorithm also in the framework of freight trains and the possibility to use the obtained georeferenced data as the input to carry out statistical analyses useful for diagnostic purposes.

5.3 Use of collected data for railway line diagnostics purposes

A statistical analysis was carried out to highlight how the acceleration data collected during the experimental campaign can be used as diagnostic indicators of the line condition. The track section taken into account to this aim is the same of paragraph 5.2 (i.e. Verona-Brennero). Collected data were processed differently with respect to what explained in paragraph 5.1. In this case, in fact, RMS of vertical acceleration belonging to the Frequency Band 1 (see Table 2) were condensed by computing the RMS over 1000 m long sections of the estimated PK and the corresponding train mean speed was determined on the same spatial windows. It was then possible to relate the obtained synthetic indices to the estimated PK subdividing them into bands of train mean speeds. The three chosen bands of speeds are reported in Table 4.

Speed Band 1	**Speed Band 2**	**Speed Band 3**
0 – 45 km/h	**45 – 90 km/h**	**> 90 km/h**

Table 4 – Definition of the train Speed Bands adopted for the statistical analysis

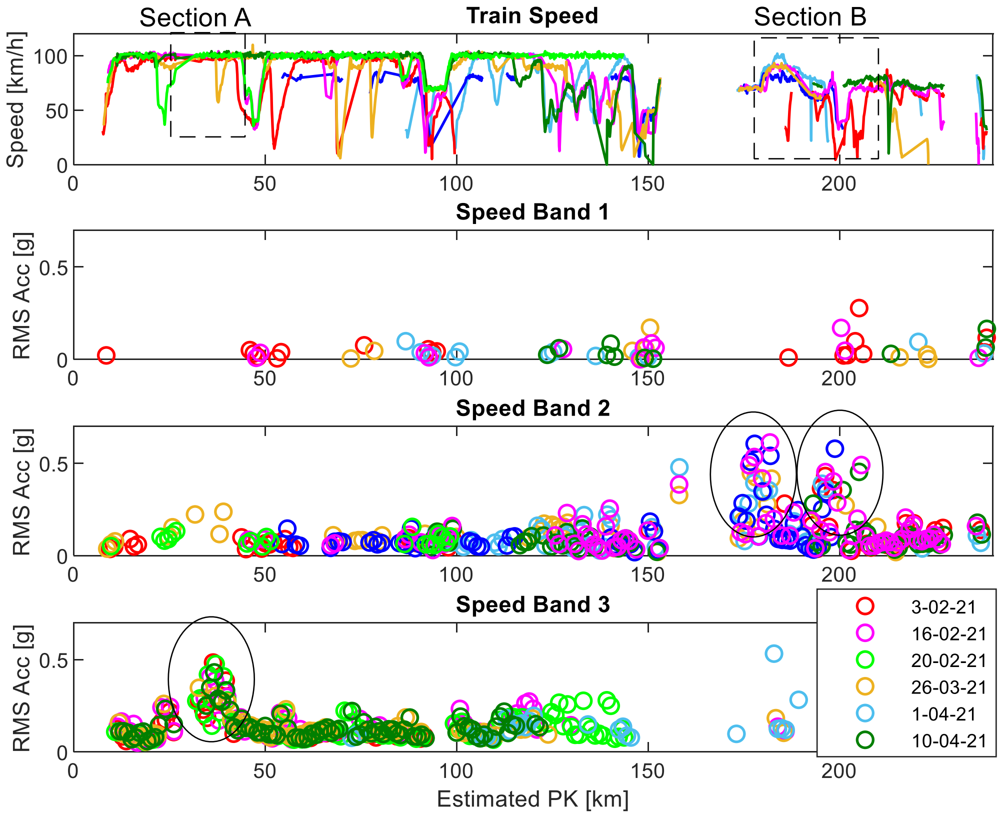

Figure 12 – Main results of the statistical analysis: diagnostic indicators on the railway track split in Speed Bands

As highlighted through black ellipses in Figure 12, from the proposed analysis comes out that some sections of the considered track (Verona-Brennero) are characterized by higher RMS acceleration values with respect to other portions. In particular, RMS peaks are considerably higher for the Speed Band 2 in the section B of the railway track, which correspond to a tortuous path in a mountain area.

Concerning Speed Band 3 instead, it can be observed the presence of high RMS peaks in Section A, which represents a small portion of the railway line travelled by the train at a sustained speed. As can be noted, both situations occur for several different travels on the same track section. The fact that high RMS values are present only in some portions of the track may indicate that the line is worn in these points. In fact, the vertical track irregularity in the wavelength range 3-25 m can be detected through the vertical RMS acceleration belonging to Frequency Band 1 (1-10 Hz), taking into account the 100 km/h cruising speed of a freight vehicle. In order to detect punctual faults such as track joints, acquisition parameters requiring a higher computational power are necessary and this implementation will be evaluated in future versions of the sensor nodes. ~~Therefore~~ In conclusion, it was shown how the collected data and the developed algorithm could be employed to perform efficiently diagnostic activities of the infrastructure.

6. Conclusions

A monitoring system composed by wireless sensor nodes was designed and developed with the aim of performing vibration monitoring and predictive maintenance on freight trains, which are still lacking this kind of devices. The system was installed on a wagon and many data were acquired through a 3-months field test. A suitable algorithm was developed in order to post-process data and to carry out their geo-localization. The map-matching technique applied to the GPS information was proved to be sufficient to obtain accurate geo-referenced vibration data along the railway line. The efficiency of the algorithm in this context was demonstrated through the analysis of data repeatability, by superimposing several travels on the same track section. Geo-referenced data were then employed in a statistical analysis showing that the developed tool is suitable to perform diagnostics activities of the infrastructure. A future perspective is represented by the development of a full wireless system able to carry out the diagnostics and predictive maintenance activities based only on GPS information. If this would be realized, it could be possible to avoid the installation of an axle-box generator and pulse counter, minimizing the interventions to be executed on the wagons.

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