infrastructures

Review

State-of-the-Art Review of Railway Track Resilience Monitoring

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Abstract: In recent years, railway systems have played a significant role in transportation systems due to the demand increase in conveying both cargo and passengers. Due to the harsh environments and severe loading conditions, caused by the traffic growth, heavier axles and vehicles and increase in speed, railway tracks are at risk of degradation and failure. Condition monitoring has been widely used to support the health assessment of civil engineering structures and infrastructures. In this context, it was adopted as a powerful tool for an objective assessment of the railway track behaviour by enabling real-time data collection, inspection and detection of structural degradation. According to relevant literature, a number of sensors can be used to monitor track behaviour during the train passing under harsh environments. This paper presents a review of sensors used for structural monitoring of railway track infrastructure, as well as their application to sense the performance of different track components during extreme events. The insight into track monitoring for railways serving traffic with extreme features will not only improve the track inspection and damage detection but also enable a predictive track maintenance regime in order to assist the decision-making process towards more cost-effective management in the railway industry.

Keywords: railway track; condition monitoring; wired sensor; wireless sensor network (WSN)

1. Introduction

Railway systems play a vital role in modern transportation systems by quickly and safely conveying large amounts of cargo and passengers. Not only the increase in passengers and freights but also the change of world climate have become the reasons that compel railway infrastructure to frequently undertake maintenance operations [1–4].

Extreme events, generally rare occurrences, may take place once a year or every 100 years. Normally, the extreme events are of high intensity with a short duration. Nonetheless, the number of extreme events is very likely to increase in magnitude and frequency, which generate impacts that can cause damage or problems to any transportation system, namely, concerning the infrastructures, operations, freights, and passengers. The effects of climate change cause slight deterioration of rail infrastructure and may affect significantly its performance when extreme events occur [5,6]. Some of the common damages in rail assets subjected to such extreme events include damaged components, track buckling, shear crack of tunnelling, and many others. These could potentially lead to progressive failure of key rail systems such as railway bridges and tunnels, turnouts and crossings, and even open tracks. It appears that about 5–10% of all failures are weather related, being mostly caused by high temperature, icing, and storms [1,3]. An increase in the frequency of high temperature occurrences will lead to more track buckling problems, which can induce hazardous derailments and other dangerous accidents.

The deterioration of rail infrastructure is a significant issue throughout the world [7]. Railway inspection is normally conducted periodically every year or several months. It may take too much time to rapidly detect faults in the track that may cause collapse or huge loss, as is the case in the prompt identification of rail defects. The railway industry needs to improve the process and decision thinking of track maintenance. Hence, condition monitoring of rail infrastructure has become important for setting proper predictive maintenances before defect and failure take place. Structural health monitoring (SHM) has been widely developed over the past decade with many civil engineering applications, such as building, bridge, off-shore structure [8,9], in order to enhance the safety and reliability [10]. Condition monitoring can reduce maintenance and its costs by detecting the faults before they can cause damage or prevent rail operations [11].

In addition, visual inspection requirements can be reduced through automated monitoring. Several sensors may be adopted for railway monitoring such as accelerometers, strain gauges, acoustic emission and inclinometers. Apart from detecting defects in rail infrastructure, other benefits of a monitoring system integrating these sensors are to determine the number of axles, number of trains, their speed, acceleration and weight, which are important for adequate management.

Wired sensor systems have been widely used for a long time in SHM. It is noted that wired systems seem to be commonly used at large scales. However, due to their own limitations, this technique requires high cost and complex installation processes that are inconvenient [12] and have led to the adoption of wireless sensor networks (WSNs) as an alternative approach [13]. Besides providing real time monitoring and alert for preventing damage and failure [14], this technique can improve the decision making process in maintenance based on failure prediction rather than on routine operations or execution of work after failure. In addition, the lower power consumption and relatively low costs of theses sensors when compared to traditional sensor technology can reduce the impact of damaged or lost equipment [15]. Moreover, WSNs have proved that they can be used under severe weather conditions, such as strong wind, storms and snow, whilst the wired traditional technique is vulnerable to damage (e.g., corrosion), vandalism (e.g., cut wire), dirt and nature elements [16]. It is also worth mentioning that WSNs offer many possibilities previously unavailable with traditional sensor technology. In terms of time, the wireless sensing units can be installed with ease and completed in approximately half the time of the wired monitoring system because they require less labor-intensive work and no special care to ensure safe placement of wires on the structure [17]. However, it is preferable to combine periodic visual inspection and a WSN condition monitoring system for maintaining railway structures, as this enables an effective periodic inspection of structures depending on the degree of importance of each monitored component based on the detailed data supplied by the WSN [13].

In this paper, the sensors that can be used in rail infrastructure monitoring are reviewed, and the benefits and drawbacks of different sensors are compared and summarized. The insight into the rail infrastructure health monitoring can assist the decision-making process for improving predictive maintenance through real time inspection. Furthermore, this will help move from scheduled preventative maintenance to a more rational predictive maintenance approach. The outcome of this study will not only improve the understanding of railway track structural monitoring but also enhance the need for future research.

2. Railway Track Resilience

2.1. Railway Resilience Assessment

Railway infrastructure is a valuable asset throughout the world as the increase of capacity is required and the investment in railway infrastructure improvement is growing. It is interesting to note that the sudden increase of rail traffic is also a major challenge as an approximate 10% reduction in road traffic means a 100% increase in railway traffic [18]. As for existing tracks, railway traffic together with the age and poor construction of railway tracks are compounded with the effects of extreme events. These lead to frequent and severe disruptions to the railway system [19]. The specific potential impacts on railway tracks caused by extreme events are as follows.

- Rail buckling due to extreme heat [5].
- Embankment and cutting slope failure caused by low temperature, earthquakes, heavy precipitation, and flooding [1,18,20].
- Rising sea level and storm surge may cause disruption to railway tracks near coastal areas [21].
- Washing away ballast by flash floods [22].

Hence, long-term preparation for managing the impacts of extreme weather events on railway infrastructure needs to be addressed [22]. An assessment of weather-related infrastructure problems during previous events needs to be identified and conducted. Condition monitoring is essential to maintaining the resilience and performance of railway infrastructure assets. This is important to maintain asset condition and create reliable train services for passengers integrated with weather forecasts to improve the weather resilience of railway infrastructure.

Moreover, there are a number of actions need to be taken following events in order to return to the normal schedule and operation as soon as possible [22].

- Critical locations should be identified.
- Assessment of damage to railway track and vehicles. Damaged components of infrastructure should be upgraded to improve resilience to future extreme events.
- Adapt and enhance the performance and capacity of future railway infrastructure according to lessons learned from previous extreme events.

Track maintenance needs to be carried out to maintain a railway asset. Even though preventive maintenance has been regularly used to determine defects and prevent damage, condition monitoring can help move from preventive maintenance to predictive maintenance as its approaches provide cost saving over routine maintenance. Predictive maintenance has been used to detect the start of a failure by forecasting using condition monitoring. To understand the behaviour and performance of railway tracks under different conditions, data obtained through condition monitoring along with computer simulations can develop the resilient design, maintenance and repair regimes in railway industry. In addition, these will help railway tracks to withstand the effects of extreme events [18].

2.2. Resilience Index

The degradation of infrastructure due to aging and rapid change in performance due to extreme events causes a sudden decrease in functionality index [23]. After this stage, the structure needs to be recovered by strengthening and maintenance to obtain the desired functionality index. It is possible to recover the structure as a new structure with higher performance to improve resilience to future extreme events as seen in curve C in Figure 1 by fixing pre-existing problems inside the system itself as seen in A. On the other hand, the structure may also have permanent losses below the pre-disaster baseline performance (curve A in Figure 1). It is noted that resilient systems need to be designed properly to increase capacity and robustness to an acceptable level after experiencing extreme events. During aging and extreme events, condition monitoring becomes an effective way to monitor the functionality index and help predictive maintenance of a structure.

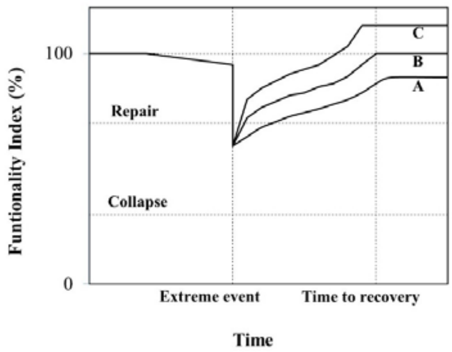

Figure 1. Functionality curve [23].

3. Railway Track Monitoring

3.1. Train Weight, Train Speed, Axle Count and Train Identification

The monitoring systems are capable of measuring train loads in order to compare their values with the legal thresholds and track capacity [24–27], but they can also provide identification of the type of train [28]. Typically, strain gauges are installed on the rails, and axle or wheel forces can be quickly estimated from their response as the rolling stock passes over the installation site. Condition monitoring can be used for train identification by measuring the number of axles of the train, their load and the distance between them [29]. The raw signals generated from the sensors are recorded as strain time series, from which the train speed and acceleration can be calculated [30].

3.2. Dynamic Impact Load and Wheel/Rail Defect

Railway track structures often experience impact loading, which is a high magnitude force of short duration. The impact load is usually caused by the irregularities of either wheel or rail [30], and it is of great importance in the design and analysis of a railway track and its components. The impact forces are significantly dependent on the train speed and may vary between 200 kN and 750 kN [31]. The dynamic wheel load is used as a design wheel load by taking into consideration the static wheel load and the dynamic impact factor, as shown in [30].

$$P_D = \varnothing P_0 \tag{1}$$

where P_D is the design wheel load, P_0 is the static wheel load and $\varnothing$ is dynamic impact factor.

The dynamic impact factor mainly depends on the train speed and type of irregularity, either in the wheel or rail. Although it can be reasonably calculated through mathematical models, due to the complexity of phenomenon, the best approach for its estimation relies on using proper condition monitoring for each scenario. Generally, dynamic loading corresponds to the frequency range between 0 and 2000 Hz due to modern railway vehicles, and it is noted that the typical duration of impact wheel forces varies widely between 1 and 12 ms [32–34]. Typical wheel-rail defects are wheel flats, out-of-round wheels, wheel corrugation, short and long wavelength rail corrugation, dipped welds and joints, pitting, and shelling, which can be identified from the monitoring data by the shape of the dynamic load signals. The real-time monitoring of wheel/rail defects based on force measurement is of paramount importance, since the high impact loading generated by these anomalies may decrease the safety levels of a railway track whose capacity is suddenly reduced by thermal effects and extreme events occurrence. For example, the capacity of concrete sleepers can be significantly reduced when the sleepers are deteriorated by excessive wear such as abrasion, in the presence of surface moisture and the case of flooding [35–37].

3.3. Track Subgrade Monitoring

Railway tracks are generally laid on a bed of ballast and sub-ballast, commonly referred as track bed, placed above a prepared subgrade layer. It is interesting to note that track bed can significantly influence the performance of the track, especially the ride quality of passenger services [38]. Thus, apart from condition monitoring of track superstructure, the track bed and subgrade layer also need to be monitored as they play important roles in providing track stability and a smooth train ride [39].

The subgrade failures in railway may arise from a variety of mechanisms, and progressive shear failure caused by high magnitude of repeated loading is the dominant factor. This can gradually lead to the large deformation and squeezing near the subgrade surface [40,41]. Another important type of subgrade failure is subgrade attrition with mud pumping. This failure causes muddy ballast and inadequate sub-ballast [42]. Mud pumping frequently occurs at spots containing fine materials and access to water, with their migration to the ballast through the voids [43,44]. This can lead to clogging of the ballast, decreasing its drainage and stress reduction capabilities.

4. Wired and Wireless Systems

Several condition monitoring systems have been implemented in civil engineering applications capable of measuring, among others key parameters, strain, displacement, acceleration, temperature, humidity and defects [16]. The periodic monitoring of the railway infrastructure is aimed at ensuring its safety. For that purpose, the conventional wired technique is still the standard method in which wires connect sensors to the acquisition units and are directly attached to the structure. Typically, the results obtained with this technique are accurate, and defects can be properly detected. However, this approach requires periodic maintenance, which added to the hard-labour installation work can lead to significant costs, resulting in the wireless techniques being more competitive with increasing popularity [12]. In fact, this alternative technology strategy can reduce the number of sensors, time for deployment, installation and maintenance costs and power consumption. Nonetheless, in general, the results obtained with wireless systems do not present the same level of accuracy when compared to those provided by wired techniques. The comparison between wired and wireless condition monitoring systems, regarding their main features, is shown in Table 1.

Table 1. Comparison between wired and wireless monitoring systems.

Wired	Wireless
Sensors are physically in contact with the structure, hence the determination of the exact position of damage is expected.	Sensors are not in contact with the structure, thus damage detection is accomplished with less accuracy than for wired systems
Greater number of sensors is needed. The wired system can become significantly complex.	Number of sensors is minimized, and their installation can be easier.
Cables can be damaged easily due to human errors or weather conditions. Hence, long-term maintenance costs can be high.	Initial cost is higher but within a life time analysis it becomes lower and regular monitoring can be achieved.
Inflexible when changes are needed, thus presenting a high time consumption when cables are to be redeployed.	Provide an easier way to physically deploy the equipment requiring shorter periods of time.

5. Wireless Sensor Network Framework

A WSN enables the continuous and near real-time monitoring of several physical systems with different levels of complexity. The proposed monitoring systems enable the collection and transmission of data from the site to the control centre [45,46], with a general framework consisting of sensor nodes, base station, and server, as shown in Figure 2.

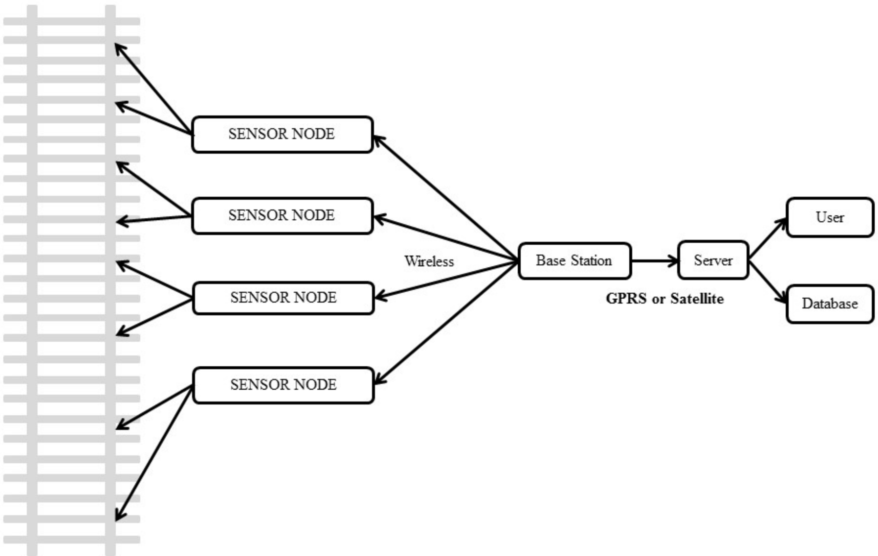

Figure 2. WSN framework [46].

5.1. Sensor Node

The sensor node generally contains a sensor, an analog-to-digital converter, a micro controller, a transceiver, power and memory [46]. One or more sensor devices embedded in different elements are mounted on boards to be attached to the monitored object, materializing strain gauges, displacement transducers, accelerometers, inclinometers, acoustic emission, thermal detectors, among others. The analog signal outputs generated by the sensors are converted to digital signals that can be processed by digital electronics, which requires a resolution of at least 16-bits to ensure results of minimum quality for structural monitoring applications [47]. The data are then transmitted to a base station by a microcontroller through a radio transceiver. All devices are electric or electronic components supported by power supply, which can be provided through batteries or by local energy generation, the latter mandatory at locations far away from energy supplies.

5.2. Base Station

The base station acts as a gateway for information transmission with the remote server. The data collected from the sensor nodes are transferred to the base station using wireless communication technology such as CAN, FlexRay, Wi-Fi or bluetooth. For example, the ZigBee network is a kind of wireless short distance communication that consumes less power [46]. On the other hand, for transmitting the data from the base station to the server at the control centre, long-range communication such as GPRS, EDGE, UMTS, LTE or satellite can be used. Due to the short transmission range, communications from sensor nodes may not reach the base station, a problem that can be overcome by adopting relay nodes to pass the data from the sensor nodes to the base station [48]. Some of the transmission data techniques available are as follows:

- Standard mobile telephony (Bluetooth, GSM, GPRS) [13], which can provide enough communication bandwidth (few hundreds Kb/s) to transmit life signals, alarm messages and possibly camera screenshots, whenever available;
- Broadband technique Wi-Fi (IEEE 802.11) [13], wireless personal area network (WPANs (IEEE 802.15.4), ZigBee (IEEE 802.15.4)) [49] or WiMAX (IEEE 802.16) [50] have higher speed and bandwidths but lower coverage and range than standard mobile telephony review;
- UMTS (Universal Mobile Telecommunications System) or Satellite links (few Mb/s bandwidth) [51] can additionally transmit a few video streams from neighbour cameras when the faults on tracks are detected by sensors in order to verify early warning in real-time;

- Fibre Optics geographic networks along the line [51,52] (only possible for fixed sites), which provide a very high bandwidth (in the Gb/s range), also allowing transmission of high-resolution videos at very high frame rates (e.g., 25 FPS) for a superior situational awareness at the control rooms.

5.3. Server

The collected data are transmitted to the control centre server through long-range communications such as GPRS, EDGE, UMTS, LTE or satellite. The sensor node may communicate directly with the control centre server without requiring the use of the base station as a gateway. Yet, for security reasons, the generated data should also be transferred to and stored at the base station where they can be accessed by the user.

6. Sensors

In terms of sensor placement, condition monitoring can be divided into two types: fixed monitoring and movable monitoring (on-board). The sensors used for fixed monitoring are installed on the railway track. The sensors can measure the condition of the whole passing train at the specific area. As for movable monitoring, the sensors attached to the train (either the vehicles or the machines) such as on the wheel, bogie, wagon, engine, etc., monitor the whole track but only at specific points of the train. The key issue with movable sensor monitoring is communication as the sensors have to move with the train along the track. The data are transmitted from the movable nodes to the fixed nodes which are in the range of transmission via satellite or GSM. However, to understand the whole section of railway track at the specific area, fixed monitoring can be used for monitoring ether superstructure or substructure. Hence, this section provides the sensor used for both track and track bed measurements.

6.1. Track Measurement

6.1.1. Strain Gauge

The most common sensor for measuring the response of structure is the strain gauge and, as its name suggests, is a device used for measuring the strain experienced by the instrumented material. This sensor is normally used in railway infrastructure for acquiring data indirectly related to train parameters such as the vehicle loads, impact forces, moving speed, axle count, identification and wheel defects [53,54]. The strain gauge can be used either for sensing the bending normal strain of the rail foot or the shear strain of the rail web. The data are converted into the loads applied at the rail head by assuming a linear elastic response under certain measurement conditions. In addition, the strain gauge is also applied for capturing lateral loads on the rail, thus enabling the quantification of lateral to vertical load ratio for train derailment early warning [55–57].

It is worth mentioning that in the study carried out by Stratman et al. [58] for detecting faulty wheels, 64 strain gauges were applied in each rail of the track, half of them for measuring the vertical load and the other half for capturing the lateral loads applied to the rail. The average force, referred to as the nominal force, and peak force were extracted from the time series data, and the ratio between these two forces was adopted as an indicator of the presence of a defect in the wheel.

Presently, optical fibre sensors are widely used as an alternative for structural sensing and health monitoring applications in composites, aerospace, marine and civil engineering [59–61]. One of the newest application areas for their use is in the railway industry. Fibre brag grating (FBG) is an optical fibre sensor capable of sensing changes in either strain or temperature of the instrumented material. The formation of permanent gratings in an optical fibre was first demonstrated by Hill et al. [62], and Meltz et al. [63] used the first interference pattern of ultraviolet laser light to create the periodic perturbation of the refractive index along the fibre length (grating). When compared to electrical strain gauges, FBGs present clear advantages such as long life time (more than 30 years), electrical immunity, ease and cost of installation. One of the first applications of FBG sensors in railways was accomplished in the monitoring system of the Tsing Ma Bridge [64,65], for measuring the temperature and structural response of cables, girders and bearings during train crossings. Another pioneer railway industry project in successfully adopting this sensing technology was carried out at the KCRC railway line in Hong Kong for detecting trains and measuring their speed and weight. The results compared well with the data supplied by a parallel electrical based monitoring system, and it was concluded that FBG sensors benefited from a simpler installation procedure.

The use of conventional strain gauge sensors can be used as guidance in instrumenting structural elements with FBG sensors, namely regarding their positioning, and assist in the analysis of the resulting signals. The position and orientation of FBG sensors can be determined from the extensive experience gained by applying their electric counterparts for measuring local deformation [66].

6.1.2. Accelerometer

An accelerometer is a sensor capable of measuring the rate of change of velocity in the instrumented body, and it can use a great number of sensing principles and technologies such as the capacitance, piezoelectricity, laser based, magnetic induction, optical, electromechanical servo-hydraulics, resonance, among others [67]. In railway applications, the vibration monitored by the accelerometer in the track can be converted into force, and then be used for detecting wheel defects or counting the number of axles (in this case a supplementary method is needed) [68,69]. Field testing has been extensively executed for validating the ability of accelerometer based condition monitoring systems to capture several train features for different passing speeds from the track vibration [70].

The accelerometers can be bonded to the web of the rail or fastened to its foot, and even attached underneath the rail itself, for sensing the passing trains. These sensors are generally placed at the rail midspans between consecutive sleepers covering an instrumented length up to 12 m or one revolution of a wheel. The main benefit of using accelerometers over strain gauges for detecting wheel defects is their ability to detect impact across the entire length of the rail between two sleepers, thus providing a more effective condition monitoring for the entire circumference of the wheel [71]. Nevertheless, a limited performance regarding repeatability for detecting damage has been identified for some conventional accelerometer-based systems [70]. However, the advantage of these systems over strain based systems is that the magnitude of the response depends in part on the wheel/rail associated with the unsprung mass [68]. Therefore, the response is independent of the vehicle mass [70].

The vast majority of conventional accelerometers are based on piezoelectric crystals, usually a major drawback because of their large size. In order to overcome this problem, a new type of sensor, named "Micro electromechanical systems (MEMS)", was first developed in 1979 to replace the conventional sensor [67]. A MEMS accelerometer is composed of a movable proof mass with plates that are connected through a mechanical suspension system to a reference frame [72]. The advantages of this type of sensor are its small dimensions, integrated devices or systems that combine electrical and mechanical components that could be produced at relatively low cost [73]. The use of MEMS in wireless monitoring system can reduce the cost significantly when compared with traditional wired sensor technologies [74–76]. It can be now concluded that previously expensive sensors can now be replaced with inexpensive, efficient, low-consuming power alternatives. Moreover, MEMS sensors are capable of operating in harsh environments for safety critical applications, characterized by extreme temperature, vibrations or shock conditions [77,78]. However, these sensors present some drawbacks [79]. Firstly, each sensor node must be battery powered, and the replacement period should be based on specific industry requirements. Secondly, the power consumption can be affected by the data transmission bandwidth which varies depending on the chosen radio frequency and transmission power. Thus, the type of data monitored and how often they are transmitted should be decided carefully.

6.1.3. Acoustic Emission

To identify crack growth, remaining life, and fatigue life of the track components, an acoustic emission (AE) sensor has been proposed as an alternative method which is very useful [73]. This provides cumulative damage information for a particular area such as inside the structure, hidden effect, micro structure, etc. The AE sensor has been widely used in many engineering applications [80] due to its capability to detect crack growth, damage accumulation and AE source localizations in many concrete structures and infrastructures. In railway applications, AE have been applied to detect faults in wheels and rails. However, only a limited number of AE tests on site have been conducted. The use of AE tests in railways has been carried out in laboratories as seen in the literature [81].

The AE technique was used for steel rail crack detection [82]. The cyclic 3-point and 4-point fatigue loadings were applied to the steel rails in laboratories. The frequency bandwidth range of AE sensors between 150 kHz and 750 kHz was used. This paper clearly confirmed that the waveforms generated by AE were related to crack propagation in rail steel [83]. In field measurements, the rolling noise produced from wheel irregularities may affect the AE waveform which had similar amplitude as crack growth. To avoid the effect of rolling noise, the wideband sensor with a bandwidth of 100 kHz–1 MHz with different gains was employed.

The AE waveform shape depends on the mode of failure. In case of tension failure, the elastic energy carrier arrives quickly, leading to waveform with a low rise time (RT), high rising angle (RA) and frequency, whereas shear failure typically occurs in a longer rise time, with lower rising angle and frequency due to the delay of the waveform energy. This is because of the rapid change in volumetric near the crack tip in the case of tension failure.

The AE technique was then adopted to a railway site for continuous monitoring [84]. The AE sensors were placed on rails continuously under different moving trains and trams located in Portugal and UK to detect wheel abnormalities. The different types and frequencies of AE sensors have been investigated; specifically, frequencies of 30 kHz, 150 kHz, 300 kHz and 500 kHz. It was noted that the distance between the first sensor and last sensor was the perimeter of the wheel. It was also noted that the low frequency sensor was mounted to detect any transient and the high frequency sensor was used for detecting waves in noisy environments. The defected and non-defected wheels were compared to ensure that the AE sensor had the potential to identify defects of wheels properly. The results showed that the periodic spikes in the graph of the AE waveform were observed in the case of a wheel flat whereas a smooth curve was observed for non-defected wheels. It was noted that AE is a diagnostic tool.

6.1.4. Inclinometer

The inclinometer is an instrument for measuring inclination or tilt. The inclinometer can be installed horizontally on the sleeper or ballast to measure the tilt [85]. In addition, an inclinometer can be mounted parallel with the track on the sleeper to measure settlement. In addition, the inclination data recorded can be used to predict the actual deflections of the track. The track movements over time, particularly where nearby construction work or where the track passes through vulnerable areas such as regions prone to landslides may affect the track settlement [45]. Moreover, inclinometers have been used to measure the tilt of the slab phase to help operators install the slab track in the right position and to periodically monitor the slab behavior in the monitoring phase [86].

6.2. Track Bed and Subgrade Measurement

In the track bed, water is expected to play a significant role in track bed failure mechanisms such as mud pumping, simply because the absence of water may prevent mud pumping. The major factors that can affect subgrade problems in the railway track are pore water pressure and water content [38,43,44]. The increase in pore water pressure results in a decrease of effective stress and the safety factor in the subgrade layer. Subgrade layers with low permeability such as clays, may have a sudden increase in pore pressure (called "excess pore pressure"). The excess pore pressure cannot readily dissipate, and this behaviour can lead to the failure of soil. Pore pressure can cause the development of mud pumping near the interface between ballast and subballast during train passage. Another factor is water content. The water content (also called "moisture content" or "soil content" in soil) is the quantity of water contained in the soil. In the subgrade layer, increased water content can significantly influence the decrease in resilient modulus. An increase in the water content from 27.1% to 30.1% can reduce the subgrade modulus by almost 50% [87]. A high water content in the subgrade later can lead to progressive shear failure. In terms of subgrade deformation, Multidepth deflectometers consisting of a number of linear variable displacement transformers (LVDTs) are installed in a borehole to measure subgrade deformation at various depths. Also, settlement probes can be used by measuring the changes in fluid pressure.

6.2.1. Water Pressure Sensors

The fluid pressure in the ground, ballast, sub-ballast, and sub-grade can be measured using water pressure sensors [38,88]. Firstly, a conventional piezometer installed below the ground water table has been used for measuring positive water pressure. A piezometer is widely used in geotechnical engineering for measuring pore pressure, determining the ground water level and the rate of groundwater flow. A piezometer is a device used to measure liquid pressure by measuring the height to which a column of the liquid rises against gravity [89]. The benefit of a piezometer is to have a fast short-term performance so that this is capable of measuring the pore pressure during the train passage. There are a number of piezometers used for measuring the pore water pressure as follows.

The first piezometers in geotechnical engineering were open standpipes (sometimes called Casagrande piezometers) [90] consisting of a filter tip and a riser pipe. The piezometer is installed in a borehole. The intake zone in a borehole is backfilled with sand and bentonite seal. The advantage of this type is its simplicity of measurement as the pore pressure obtained can be read easily via the water level in the riser pipe. However, there are drawbacks of using this type of piezometer. It is difficult to install under an existing sleeper, which is the location of high pore pressure, because the piezometer requires a vertical borehole. In addition, the borehole can affect subgrade deformation due to the large diameter of the borehole. Although the casagrande piezometer has a good long-term reliability, it may take a long time to saturate for fine-grained ground.

The vibrating wire piezometer [91], which is suitable for most applications, is the most commonly deployed type of piezometer. The results obtained are converted from water pressure to a frequency of vibrating wire. Hence, the change of pore water pressure causes the diaphragm to extend or relax, causing changes in the wire stress and natural frequencies. The advantages of a vibrating wire piezometer are the high accuracy of results and the immunity against noise while transferring data over a long cable. Nevertheless, this is not immune to electrical problems normally associated with electronic instruments. The water pressure obtained can be read by data loggers or portable readout units, allowing faster or more frequent readings than standpipe piezometers.

Apart from these piezometers, there are a number of piezometers used in geotechnical engineering such as pneumatic piezometers, hydraulic piezometers, and titanium piezometers [92] that provide different benefits and drawbacks. However, the piezometers used for subgrade monitoring in railway application are standpipes piezometer and a vibrating piezometer.

Secondly, a water pressure sensor called a "tensiometer" measures the negative pressure or water tension in partially saturated zones [38]. This sensor can be installed over the ground water table. The device consists of a tube with a porous ceramic cup and is filled with water. A WSN early warning system was developed for landslides using tensiometers [93]. Tensiometers are able to detect changes in pore pressure rapidly to warn of slope instability, whereas reflectometers detect water content changes over time to warn of wet soil slippages.

The piezometer has to be installed in the critical area that contains high stress such as near the interface between the ballast and subgrade. However, even though the sensors were placed at 5 cm below the interface, the sensors could be destroyed by high traffic stress [88]. The precipitation, soil water content and pore pressure were monitored continuously over a year in order to provide an early warning system for landslides related to weather conditions for rail traffic between Seattle and Everett, Washington, USA. It was noted that pore pressure had a greater influence on the slope instability than the water content so water pressure sensors were used for measurement. Piezometers provide little useful information in unsaturated zones. Therefore, a tensiometer can provide better results in the change of pore pressure in partially saturated and unsaturated zones [93].

6.2.2. Multidepth Deflectometers (MDDs)

The technology of Multidepth deflectometers (MDDs) was first introduced to measure the deformations in pavement under truck loading [94]. MDDs consisting of a number of linear variable displacement transformers (LVDTs) are installed in a borehole drilled vertically to measure the deformation of sub-structure layers at various depths. The MDD anchor needs to be fixed in the non-deformable soil layer which is normally located at a depth of 3 m below the top of the sleeper. According to previous studies [95], to monitor the deformations of each layer of railway track, LVDTs were placed in the borehole at various depths: at the top of the ballast layer, top of the subgrade layer, top of the embankment fill layer, top of the upper subgrade layer and top of the lower subgrade layer, and the anchor was placed in the lower subgrade layer. However, the installation of MDDs is difficult under a railway track as the size of MDDs is large [38].

6.2.3. Settlement Probes

The measurement of the vertical deformation is made by measuring the changes in fluid pressure in the sensor end relative to a fixed fluid head datum (reservoir) [38,88]. The settlement probe consists of a reservoir on one end and a pressure transducer which connects to the reservoir via small tubing embedded in the ground. The settlement probe applications are to monitor settlement in subsoils, foundations, and embankments.

The benefits of liquid-based settlement probes are that they are small and cost effective. Moreover, this has a high flexibility for installation and placement because the probe can be installed at any depth and orientation while the head datum is fixed. Hence, this can be easily installed in the subgrade layer while maintaining a reliable point of reference on the ground. However, the selection of a pressure transducer is important as it indicates the performance of the settlement probe. Hence, long-term offset stability and temperature sensitivity transducers are needed to deal with the long-term drift in railway tracks [88].

A number of improved sensors were installed in the subgrade layers [38]. Piezometers, accelerometers, liquid-based settlement probes and temperature sensors were installed at a busy high speed Northeast Corridor (NEC) railway site. The track degradation can be measured from the increase of peak acceleration response of the subgrade layer during train passage. The track acceleration can indirectly represent the maximum force induced by a train. It was noted that the track deterioration had a greater acceleration response than newly aligned ones.

The piezometers measured the long-term variation of pore pressures and train-induced pore pressures. The MEM accelerometers installed at the sleeper and top subgrade were used to measure high-frequency wheel induced acceleration response using a high frequency data acquisition system (10 kHz sampling rate). The liquid-based settlement probe installed at the top of the sleeper was used to measure the vertical deformation in the subgrade layer. The temperature sensors installed at the top subgrade, deep subgrade and sleeper were useful for investigating the effect of temperature, freezing and thawing on track degradation. The objectives of each sensor are outlined in Table 2, and the placements of each sensor are discussed in detail in the next section.

Table 2. The objectives of the sensors for railway track monitoring.

Objective	Sensor	Placement
Train speed, acceleration	Strain gauge Accelerometer	Rail Rail, sleeper, railbed
Train load, dynamic load	Strain gauge Accelerometer	Rail Rail, sleeper, railbed
Settlement	Inclinometer LVDT Settlement probe	Rail, sleeper, railbed Rail, sleeper, railbed Railbed
Wheel-rail defect	Strain gauge Accelerometer Acoustic emission	Rail Rail Rail
Soil water content, pore pressure	Piezometer Tensiometer	Railbed Railbed

7. Sensor Placement

The positions of sensors used for track monitoring are shown in Figure 3.

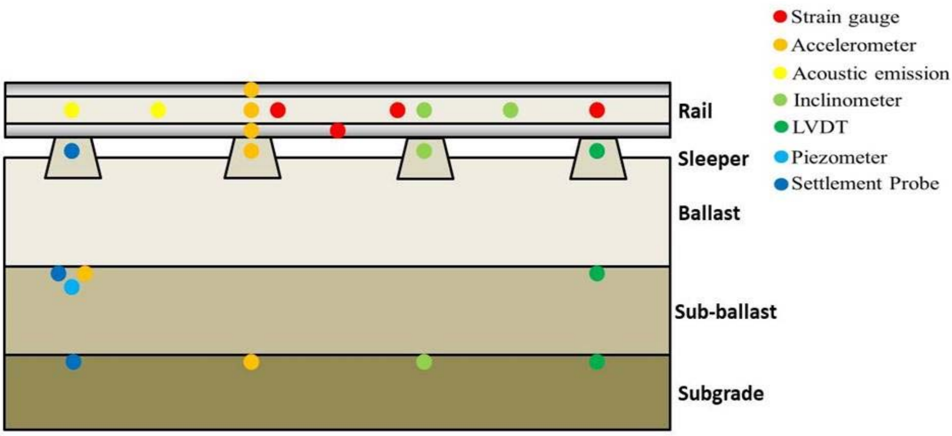

Figure 3. Schematic location of the sensors used for condition monitoring.

The two strain gauge sensors are located in the rail web with an angle of 45° with respect to the rail neutral fiber to monitor dynamic load [29]. The strain gauge sensor placed in the position rail web above a sleeper in the vertical direction only considers the compression suffered by the wheel load. Moreover, a strain gauge can be installed at either the rail foot or rail web to identify the train [27].

Accelerometers were mounted in different positions on the rail [71]. Accelerometers can be installed on the top of the subgrade layer to measure how the load and acceleration magnitude transmit from the sleeper to the subgrade layer via ballast and sub-ballast layers [88].

Acoustic emission can be installed at various positions on the rail to detect crack growth on rail and wheel defects. It was noted that placing many AE sensors along the rail track can possibly detect wheel defects [89–92,96].

Inclinometers, installed horizontally on sleepers and ballast, have a role in measuring the tilt. In addition, an inclinometer can be installed horizontally in the subgrade layer to measure the settlement profile by integrating the tilt angle along the borehole with respect to the reference point [38].

In order to record transient and permanent vertical displacement, LVDTs can be used by installing LVDTs at various depths in a borehole [97]. The LVDT installed at a sleeper measures the response of a sleeper to the ballast layer. The LVDTs installed in a borehole at the ballast/sub-ballast and sub-ballast/subgrade interfaces measure sub-ballast and subgrade responses, respectively.

The piezometer can be installed at any depth of soil. However, the top of the sub-grade was considered as a good place for the sensor because this is the critical location that contained peak pore pressure [91,98]. The pore pressure can easily dissipate from the subgrade to the ballast layer during the train passage. After installation, the hole was backfilled by in situ soil [38] Moreover, a settlement probe can be installed easily through a diameter hole by auger at any depth and orientation. This has a high flexibility for installation and placement [88].

8. Conclusions

This paper presents an overview of railway track condition monitoring and the definition and functions of sensor requirements. The main aims of railway track monitoring are to identify the possible damage, provide real time condition, improve safety and reliability, and help move from scheduled maintenance and preventative maintenance to future predictive maintenance. The recent research advances on the use of sensors for railway track measurement have been reviewed. Presently, wireless sensor networks have sometimes been being used instead of conventional wired systems as they provide more benefits in terms of cost and ease of installation process. Moreover, this technique shows good performance in extreme events. However, the difficultly with the wireless system is the transmission process from sensor to base station and then to server as it consumes high energy. The comparisons between wired and wireless systems have been discussed. The sensors used in both the structure and sub-structure of railway tracks, such as strain gauge, accelerometer, piezometer etc., have been reviewed. It can be seen that the sensing technology has been developed in order to tackle the effect of the environment. The sensors for subgrade measurement have also been discussed because this area also has a significant effect on track behaviour. Due to the increase in traffic and load demands, damage detection in railway track will become more significant because railway tracks and its vulnerable components will have more sensitivity to train load and harsh environments. In the future, more data will be collected and the number of sensors used might increase due to the increase in extreme events in the wider area. Therefore, the energy efficiency and transmission mechanisms must be developed in order to provide reliable and consistent communication for further requirements. The insight information can be used to improve track monitoring for condition-based track maintenance.

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