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A Review on Existing Sensors and Devices for Inspecting Railway Infrastructure

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ABSTRACT

This paper presents a review of sensors and inspection devices employed to inspect railway defects and track geometry irregularities. Inspection of rail defects is an important task in railway infrastructure management systems, and data derived from inspections can feed railway degradation prediction models. These models are utilised for predicting potential defects and implementing preventive maintenance activities. In this paper, different sensors for detecting rail defects and track irregularities are presented, and various inspection devices which utilise these sensors are investigated. In addition, the classification of the sensors and inspection devices based on their capabilities and specifications is carried out, which has not been fully addressed in previous studies. Non-Destructive Testing (NDT) sensors, cameras and accelerometers are among sensors investigated here. Correspondingly, trolleys, Condition Monitoring Systems (CMS), hi-rail vehicles and Track Recording Vehicles (TRV) are among major inspection devices that their capabilities are studied. Furthermore, the application of new devices, including smartphones and drones, in railway inspection and their potential capabilities are discussed. The review of previous and recent approaches shows that CMSs are more cost-effective and accessible than other railway inspection methods, as they can be carried out on in-service vehicles an unlimited number of times without disruption to normal train traffic. In addition, recently smartphones as a compact inspection device with a variety of sensors are employed to measure acceleration data, which can be considered as an indicator of rail track condition.

Keywords: Railway; Non-destructive; Condition Monitoring; Sensors; Inspection

INTRODUCTION

Railway networks play an important role in the economic development and sustainability of countries around the world. Investment in railway systems has increased in several countries. Rail infrastructure owners in different countries are spending millions of dollars to develop new rail infrastructure and to prevent the failure of current facilities. Along with massive demand for the use of railway transportation, railway infrastructure is subjected to intensive pressure, stresses, shear forces and lateral forces. Therefore, railway systems as one of the major means of transportation must be monitored and assessed effectively and regularly (Lidén 2015). Timely inspection of railway infrastructure and preventive maintenance are considered as two major tasks to keep railway infrastructure safe and operational. Without appropriate inspection and maintenance planning, the risk of failure in railway networks increases, which may lead to catastrophic human casualties and massive financial losses. Inspection is the prerequisite of railway preventive maintenance, which can help operators and decision makers to observe the condition of the railway infrastructure and make them aware of potential hazards (Uzarski & Grussing 2013; Kacunic & Car 2016).

The history of rail inspection dates back to more than a hundred years ago when inspections were carried out visually without automated applications. In later years, mechanical sensors were applied to measure track geometry parameters. The electromagnetic technique was one of the primary tools for inspecting rail internal defects in high-speed networks until 1953, when ultrasonic transducers were introduced to railway inspection. Since then, various inspection methods have been used for monitoring the health of railway infrastructure or as a preventive measure against rail failures (Popović et al. 2015). Different types of fault detection sensors and inspection devices have been examined separately in various railway studies. However, limited studies attempted to perform classification and comparison of the capabilities and limitations of these sensors and devices in railway systems. The aim of this study is to fill this gap by investigating and examining relevant previous studies.

In the second section, various sensors for inspecting rail defects are explained and classified based on their ability to capture different type of rail defects. At the end of this section, comparison of the sensors are provided. In the third section, different railway inspection devices and vehicles which utilise single or a combination of sensors are explained and classified. Furthermore, the role of innovative applications for measuring the condition of rails and tracks such as Condition Monitoring Systems (CMSs), smartphones and drones are examined. The capabilities and drawbacks of these applications are summarised at the end of this section. Finally, a discussion and conclusion are presented.

SENSORS FOR DETECTING RAILWAY DEFECTS AND TRACK IRREGULARITIES

In this section, different sensors for detecting rail defects, track geometry irregularities, defective wheels and capturing acceleration data (ride comfort) are investigated. These defects can be categorised more precisely into internal rail head defects, rail web/foot defects, near-surface defects, surface defects (rail corrugations, squats, surface cracks), defective wheels and bearings (hot wheels and hot bearings), rail profile irregularities (rail wear and rolling contact fatigue) and track geometry irregularities (gauge, twist, cross-level, longitudinal level and alignment). Sensors for detecting such defects can be categorised as Non-Destructive Testing (NDT) sensors, cameras, optical lasers, accelerometer transducers, mechanical sensors and complementary sensors. In the following sections, these sensors along with their capabilities and drawbacks are described. Figure 1 illustrates the relationship between different sensors and their capabilities to detect various rail defects and track irregularities.

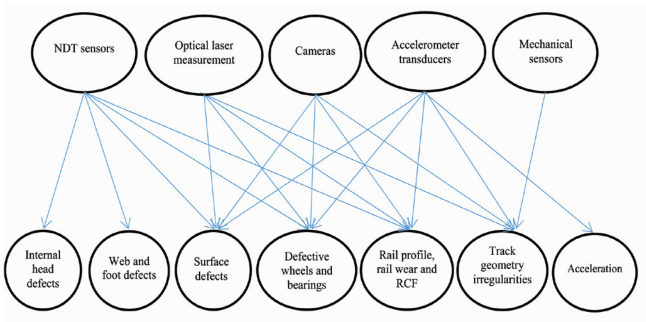

FIGURE 1. Relationship between sensors and different railway faults

NDT SENSORS

NDT sensing is one of the wide group of inspection techniques applied in industry and technology to assess the properties of a component or a system without causing damage. In railways, different sensors and techniques, including Ultrasonic Testing (UT), Eddy Current (EC), Magnetic Flux Leakage (MFL), Acoustic Emission (AE), Electro Magnetic Acoustic Transducers (EMATs), Alternate Current Field Measurement (ACFM), radiography, microphone and thermal sensors are categorised under NDT sensors. These sensors are able to detect a wide range of defects, including surface defects, near-surface defects, internal defects, rail-web defects and rail-foot defects.

In UT, sound waves at frequencies above audible wavelengths are provided. These waves have the capability to detect the presence of internal defects (Moynihan & English 2007; Safa et al. 2015). EC testing relies on the electromagnetic-based interaction between the currents induced in the metallic material and the magnetic field of a test probe. The combination of UT and EC inspection improves the probability of early detection of defects (Papaelias et al. 2008; Dey et al. 2016). The basic principle of MFL is that a strong magnet is applied to magnetize the railway infrastructure. At areas where there is any geometrical discontinuity or missing metal, the magnetic field leaks into the air, enabling the defects to be imaged (Li et al. 2007). AE is a passive non-destructive evaluation method, where the sensors do not produce an interrogating signal but their function is to detect signal emissions that are generated from the defects (Papaelias et al. 2008; Kabir & Alsulami 2015). The EMAT technique can be used to generate and detect ultrasound in magnetic or electrically-conducting materials by transferring a large current pulse provided by a permanent magnet (Papaelias et al. 2008; Han et al. 2014). The ACFM technique is based on the principle that an Alternate Current (AC) can be produced to flow in a thin layer close to the surface of any conductor and is not sensitive to the overall geometry of the component (Gao et al. 2015).

Digital radiography is an economical method for inspecting the internal flaws of rails. Today, the use of X-ray radiography has become more prevalent. This type of inspection is used as a means of verification in places where rail defects have already been detected or in areas such as switches where inspection using other methods is unreliable (Kabir & Alsulami 2015). A microphone or acoustic sensor is an electronic device designed to listen to rail corrugations and identify defective wheels. Acoustic sensors differ in terms of their sensitivity, frequency bandwidth and other dynamic characteristics (Tondon & Choudhury 1999; Thompson et al. 2015). Lastly, infrared thermometers are designed to monitor the temperature of some specific railway components in order to predict defects in advance. In this type of sensor, acceptable ranges of temperature variation can be set and any value exceeding the threshold will trigger alarms and inform operators of the potential failure of components (Campos-Castellanos et al. 2011).

CAMERAS

High-resolution cameras and thermographic cameras are widely used today as probes in railway inspections. The data collected by cameras are the input for automatic visual inspection systems which by applying image processing techniques, can identify different types of railway defects such the percentage of wear of the rail head, broken turnout frogs, rail profiles, corrugations, track gauge, and missing bolts. Image processing has three main elements: data acquisition, image analysis and pattern recognition. In pattern recognition, images and videos are processed precisely using machine-learning algorithms and deep learning techniques. Thermographic cameras or thermal imaging cameras form an image using infrared radiation. This type of camera shows the hidden heat patterns that point out structural defects and other problems in railway components. The higher a component's temperature, the more infrared radiation is emitted (Minbashi et al. 2016).

OPTICAL LASER MEASUREMENTS

The non-contact optical laser-based measurement system is an effective measurement tool for capturing different track geometry parameters, rail profiles, rail wear, Rolling Contact Fatigue (RCF), and defective wheels. This sensor generally operates based on the time of flight principle. To calculate distances and track geometric parameters, the sensor emits a narrow beam light towards the desired object and measures the time taken by the pulse to reflect off the target and return to the device. Light Detection and Ranging (LiDAR) is an optical laser measurement technique which is used in railway inspection for the detection of surface rail defects. By sending ultraviolet and near-infrared light, this technique can produce high-resolution maps of objects with 3-D representations. This sensor can also be used as a wayside detector to identify truck rotation, tracking errors and inter-axle misalignment. Providing the measurement at a relatively high speed is the main advantage of this sensor (Li & He 2014).

MECHANICAL SENSORS

This type of measurement was among the first methods used to measure track geometry parameters. In this method, a movable roller object, which has constant contact with rails, is used to indicate track geometry parameters. This roller simulates the passage of railway wheels. This system can be mounted on Track Recording Vehicles (TRVs) and hi-rail vehicles to capture track geometry parameters continuously, or it can be mounted on a trolley pulled by a human operator. This type of rail inspection technique is simple and cheap. The major drawbacks of these sensors are their low accuracy and inability to inspect the parameters at high speeds, as the sensor may not maintain constant contact with the rails (Barke 2005).

ACCELEROMETERS

An accelerometer is an electromechanical sensor designed to measure vertical and horizontal acceleration signals derived from vibrational forces in mechanical variables. In railways, these vibration forces can result from the presence of defective wheels, rail wear, damaged switches or track geometry irregularities. By applying a series of mathematical computations, rail defects and track irregularities can be measured from acceleration data. Accelerometers have been used in different railways inspection devices such as wayside detectors, TRV, CMS, axle box measurement, and they have been embedded in smartphones as well. Compared to other sensors, accelerometer sensors can provide more inspection points in a certain length of a track. Furthermore, recently accelerometers have been used for measuring ride comfort in public transportation fleets (Li et al. 2017).

COMPLEMENTARY SENSORS

GPS and gyroscopes are two important sensors which have been used as complementary sensors in railway data collection practices. A GPS sensor is a receiver which, by communicating with a global navigation satellite system, can provide real-time geographical location and time information to an end-user anywhere. Today, GPS sensors are utilised in different railway inspection applications such as trollies, TRVs and CMSs. Gyroscope sensors embedded in inspection applications are used to measure the rotation of vehicles in three angular directions. Rate gyros are designed to indicate the rate of change of angle with time instead of indicating the direction only (Durazo-Cardenas et al. 2014). Table 1 provides a summary and comparison of the above sensors and their capabilities to detect railway defects, their detection speed and their major disadvantages.

INSPECTION DEVICES AND VEHICLES

Railway inspection devices and vehicles are designed to detect a wide range of rail defects. Their capabilities can be varied based on the rail sensors installed on them. These devices can be divided into two main categories: wayside (track-based) detectors and movable detectors, as classified in Figure 2. Wayside detectors are designed to inspect defects related to wheels and axle bearings. In wayside detectors, sensors are attached to the track or positioned at a certain distance from the track. Movable detectors can inspect and monitor rail and track conditions while the train is moving. Movable detectors can be categorised into different groups including trolleys, Hi-rail vehicles, CMSs, TRVs, drones and smartphones. In this section, different examples of the application of these devices in railway inspection practices are investigated.

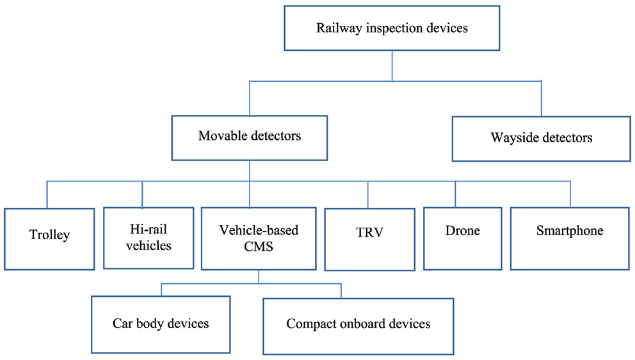

FIGURE 2. Different types of railway inspection device

WAYSIDE DETECTORS

The main purpose of using wayside detectors is to ensure the smooth running of rail vehicles and to avoid any sudden disruption on the railway line (Kouroussis et al. 2016). Depending on their purpose, wayside detectors are equipped with different types of sensors, such as accelerometers,

TABLE 1. Summary and comparison of sensors applied in railway inspection

Method	Types of defects	Detection speed (km/h)	Major drawbacks
Ultrasonic	Internal defects, web and foot defects, surface defects, defective wheels and bearings, rail wear	Up to 100	✓ Can miss defects at high speed and can miss defects smaller than 4 mm ✓ Unusable in situations where the surface of rail heads is extremely damaged or extensively worn
EC		Up to 100	✓ Lift-off and grinding marks can limit performance ✓ Unable to determine the depth of defect directly
MFL		Up to 35	✓ Can miss defects at speeds higher than 35 km/h and can miss defects smaller than 4 mm ✓ Not useful for detecting rail foot corrosion and deep internal cracks
EMAT		< 10	✓ Limited performance at low speed and lift-off variations ✓ Not strong enough to separate signals from noise
ACFM		Up to 35	✓ Cannot quantify accurately squats and short wave-length corrugations
AE		Up to 15	✓ Limited performance at high levels of external noise
Radiography	Internal defects	Static test	✓ Health and safety concerns ✓ Sensitivity decreases with increasing thickness
Microphone	Surface defects, defective wheels, defective bearings	> 100	✓ Other sources of noise can limit performance
Thermal sensors	Hot wheels and bearings	> 100	✓ Sensitive to dust and pollutants
Mechanical sensors	Track geometry parameters	< 10	✓ Very sensitive to roller fluctuations ✓ Low accuracy compared to other sensors
Optical laser measurement	Surface defects, defective wheels and bearings, rail profile and track geometry parameters	> 100	✓ Laser sensors are sensitive to environmental dirt ✓ Harsh movement can decrease sensitivity
Cameras defective wheels	Surface defects, rail profile,	> 100	✓ Pollutants and roughness can reduce the accuracy of conventional cameras ✓ Price of thermographic camera is high
Accelerometer	Surface defects, defective wheels and bearings, rail profile and track geometry, ride/comfort data	> 100	✓ Interpreting acceleration data to an accurate displacement measurement ✓ Geometric data requires complicated data processing

digital cameras, microphones, ultrasonic sensors and thermal sensors. Some successful examples of the application of these detectors are provided as follows:

1. Wheel Profile Monitoring Systems (WPMSs) are detectors installed on the track to measure wheel profiles according to the measurements of a new wheel profile. Most current WPMSs employ non-contact techniques to monitor the wear on the wheel as the train passes. A series of laser line and high-speed digital cameras are used to capture images. Then, specialised computer software packages are used to extract the wheel parameters (for example, flange width and height, rim thickness and tread hollow) to measure the wheel profile and identify cracks. More details can be found in Moynihan and English (2007) and Ngigi et al. (2012).
2. Wheel Impact Load Detectors (WILDs) are used to detect the presence of a defective wheel, and to measure the magnitude of axle load and compare it with predefined thresholds. WILD sensitivity depends on optical sensors and the accuracy of accelerometers which detect and measure wheel defects. Deformation characteristics of rail wheels such as flat spots, out-of-round or shelling conditions cause excessive impact and force on the rail and can lead to tear and wear on the track and vehicles. In this type of detector, the rail deflection caused by the vertical forces exerted by the wheels is calculated and analysed to examine wheel tread irregularities (Ngigi et al. 2012).
3. Tread Condition Detectors (TCDs) employ ultrasonic sensors to detect the presence of any discontinuity and cracks on the tread surface of the wheel. The ultrasonic waves generated by the detector transducers are transmitted to the wheels, and if there is any crack or surface breakage, the signal is sensed and detected by

the transducers. Conventional TCDs work as trains pass at speeds of 10 km/h or less. More details and examples of these applications can be found in Alemi et al. (2017).

4. Hot Bearing Detectors (HBDs) are devices used to detect unusual hot wheel bearings. By using sensitive resistors and based on infrared radiation, thermal sensors extract heat waves from the wheel bearings to discover any indication of failure. These detectors are designed to provide thermal data on bearings when the train is travelling. New systems employ digital processing of infrared images to provide higher operating speeds and attain more precise temperature measurements. The same technology is used for the detection of hot and cold wheels, which can result in brake failure. More details can be found in Newman et al. (1989) and Barke (2005).
5. Acoustic Bearing Detectors (ABDs) are employed to record the characteristics and quality of the sound made by bearings as the train moves. These detectors are based on the principle that wheel bearings produce noise and excessive vibration when they start to fail. Various measurement techniques, such as sound intensity, sound pressure and AE, can be employed by these detectors. Compared with hot axle bearing detectors, this type of detector is more developed as it is highly sensitive and is able to predict failed bearings in advance. Recent ABDs can detect more than one-third of hot bearing failures. More details can be found in Li et al. (2014).
6. Trackside Acoustic Detection Systems (TADSs), which are equipped with multiple (trackside) microphone arrays, identify different types of bearing flaws (tapered roller bearings and spherical bearings) in freight and passenger cars as they pass at operating speeds. This system can identify defects early in the growth cycle, reduce hot bearing train stops and delays and allow for scheduled maintenance. The system can provide users with warnings of defects and severity information. The collected data can then be transferred via the Internet or special files (Anderson 2007).
7. The Brake Pad Measurement System (BPMS) is a type of non-contact detector which functions based on digital images from cameras and machine vision technology. The purpose of this detector is to calculate the thickness of brake pads and identify problems related to brake pads, such as wear rates, uneven wear and missing brake pads. In this type of detector, high-speed digital cameras are installed beneath the track to inspect the condition of the brake pads and provide precise profiles of the components (Ngigi et al. 2012).

MOVABLE DETECTORS

These detectors can be classified as trolleys, hi-rail vehicles, TRVs, CMSs, smartphones and drones. Descriptions and successful experiences of movable detectors are provided as follows:

1. *Trolleys*

Trolleys are cost-effective manually operated tools used to inspect rail and track infrastructure. Due to their compact design and small overall dimensions, it is easy to place them on or off the track to allow approaching trains to pass. Trolleys can be equipped with different sensors, such as UTs, mechanical sensors and laser measurement systems to inspect railways for rail wear, rail profiles defects and track geometry irregularities. Furthermore, trolleys can be combined with a PC and GPS to store collected data and determine the exact location of measured data. The main difference between a trolley and other inspection applications is their speed, which cannot be compared with that of hi-rail vehicles and TRVs. Recent trolleys equipped with advanced optical laser measurement systems have been successful in capturing track geometry parameters. Due to the capabilities of this type of inspection, they are suitable for limited sections of a railway network. For more details refer to Engstrand (2011) and Evans et al. (2018).

2. *Hi-rail vehicles*

A hi-rail vehicle is an inspection vehicle which can operate both on rail tracks and a conventional road. They are often converted road vehicles, with additional flanged steel wheels for running on rails. This ability of hi-rail vehicles increases their flexibility of deployment. As the speed of this type of vehicles is limited, they must be run when the rail line is closed to normal train traffic. hi-rail vehicles can be equipped with different types of sensors, such as optical lasers, UTs, ECs and EMAT sensors for detecting rail defects and measuring track geometry parameters. hi-rail vehicles can be programmed to work automatically as self-propelled vehicles or driven by an operator. Due to the capabilities of this type of inspection, they are suitable for medium-scale railway lines. Top speeds lower than commercial trains and carrying out railway inspections without a similar loading compared to normal trains are the main drawbacks of this vehicle. More details of hi-rail vehicles can be found in Clark (2004) and Gibert et al. (2017).

3. *TRVs*

TRVs are special self-propelled or drivable rail vehicles without the need of an onboard crew designed to capture rail defects and track geometry irregularities. They can be equipped with sophisticated sensors, such as optical lasers, high-resolution cameras, UT and EC sensors. Compared to trolleys and hi-rail vehicles, TRVs are more advanced and mature to deal with different conditions and defects, but their high cost is their major disadvantage. Recent TRVs can operate at speeds up to 250 km/h. In addition to a data collection unit, they are equipped with analytical units, such as image processing and data processing to identify rail defects and collect the related information, such as the name and location of defects. Furthermore, this type of track inspection application can store large amounts of data and can be used as a long-term maintenance planning system. Advanced TRVs use cellular services and web reporting tools during their real-time inspections, which allows the instantaneous reporting of measurement data and track defects to railway track administrators or maintenance crews. Because of the capabilities of TRVs, they can be used for carrying out inspections throughout a railway line without limitations. More information about TRVs can be found in Moynihan and English (2007), Westgeest et al. (2011) and Chen et al. (2018).

4. *Vehicle-based CMSs*

CMSs are a type of movable track detector designed to capture various track defects. In contrast with TRVs which work separately from in-service vehicles, they are mounted on in-service vehicles. CMSs can be categorised into compact on-board devices and car body devices. In compact on-board devices, all sensors and system components are housed and connected to each other in a compact body. In car body CMSs, sensors and especial accelerometers are installed on different parts of the car such as the car body, the axle box and bogies. Different examples of CMSs are presented in the following section.

Elia et al. (2006) designed a car body CMS for estimating wheel-rail contact geometry parameters based on acceleration measurements on Italian high-speed railway networks. Different factors, such as gauge narrowing and rail inclination, can lead to wheel-rail contact geometric alterations, particularly in the presence of worn wheel profiles. By employing accelerometer transducers, lateral vibration is extracted and used to calculate wheel-rail contact geometry parameters. For the evaluation of the system, the methodology was applied to experimental data measured by a TRV during test runs on a high-speed line. The experimental train consisted of ten cars, including two locomotives and eight trailer coaches. The sensors were mounted on car body, bogie and axle-box. The gathered signals were completed by the train speed and position from a GPS system. The results of the experiment showed consistency between the detection of the proposed CMS and those detected by a TRV.

Bocciolone et al. (2007) developed a car body CMS on standard operating bogies for carrying out quick rail inspections. This research mainly focused on short-pitch corrugation which often occurs at small radius curves at very high rates. The experiment reported in this study was carried out in a train used on the Milan subway, and consisted of three cars: the first and last cars were motorised, whereas the middle car was a trailing one. Two accelerometer transducers measuring the vertical and lateral accelerations were installed on each axle-box of a bogie. Vertical accelerometers are mainly sensitive to corrugation, while lateral accelerometers can sense any probable lateral discontinuity, such as damaged switches, curve rail wear or the presence of localised lateral defects. According to the results of the experiment, the proposed CMS was successful in detecting short-pitch corrugation which mostly occurs on the internal rail of a curve.

Molodova et al. (2011) conducted research on the use of axle box acceleration data for measuring and detecting short track defects. The technique can indicate short track defects (defects with lengths less than about 3m) like squats, welds with poor finishes and corrugation. Since Axle Box Acceleration (ABA) is a measure of the vibration signals of the wheel in the track-vehicle system, it can provide an indication of irregularity at the rail-wheel interface. The ABA measurements employed in this research were recorded on a Dutch ICR-type passenger car. Each data set consisted of four vertical ABA signals, recorded on the axle boxes of one bogie. GPS was used for determining the location of the defects, and the train speed. Based on the results of this study, except for welds, the correlation between ABA magnitude and light squats and corrugation was in a good agreement.

Mori et al. (2013) studied the development of a compact onboard device for condition monitoring of railway track. The device needs only be placed inside a cabin to enable vehicle measurements. This method can detect corrugated rails and estimate riding comfort by determining car-body vibration and evaluate track condition effectively. The system comprised a CPU, a microphone for detecting rail corrugation, an accelerometer for detecting track irregularity, a GPS receiver for detecting the position, a rate gyroscope and a computer system for data analysis. The proposed system has some advantages over conventional systems, as it is much more compact, and has full automatic data collection and data transfer via a cellular phone. In this research, after gathering the data, the communication unit conveyed the collected data to a dedicated data server. At the data server, by applying data analysis, diagnosis of track condition was performed.

Wei et al. (2016) developed a car body CMS based on in-service vehicle acceleration measurements to detect track irregularities. In the experiment carried out in this research, the experimental equipment was implemented on the three motorized vehicles. In this system, four acceleration sensors are mounted on the bogie frames to capture short and middle term wavelength track irregularities of the right and left tracks. In addition, four acceleration sensors are mounted on the car body floor just above the four-wheel sets to measure the middle and long-wave track irregularities. After collecting data from the sensors, the measured data are transferred to the track inspection system to calculate rail track irregularities. For the evaluation of the proposed system, the outcomes were compared with those calculated by a TRV. This research concluded that the proposed track inspection system obtained a very competitive result compared to the TRV.

5. Smartphones

Smartphones are mobile phones with an operating system with extra features and sensors compared to basic mobile phones, including GPS, an accelerometer, a camera, and internet connection. The combination of different sensors has made smartphones a cost-effective probe which can be used to collect acceleration data, gyroscope and GPS data in railway vehicles, mostly for measuring ride comfort. In railways, ride comfort which is extracted from the acceleration signals can be considered as an indicator of different conditions such as track irregularities, infrastructure quality and rail/

wheel contact forces. In this section, the application of smartphones in capturing data for the purpose of ride comfort is presented.

Simonyi et al. (2014) assessed passenger ride comfort in public transport modes in Budapest. In this research, a smartphone with built-in GPS and accelerometer was employed, and ISO 2631-5 (2004) was chosen to assess the effect of vibration on passenger comfort. The standard defines six different comfort levels based on acceleration measurement: not uncomfortable (0 m/s^2 -0.315 m/s^2), a little uncomfortable (0.315 m/s^2 – 0.5 m/s^2), fairly uncomfortable (0.5 m/s^2 – 0.8 m/s^2), uncomfortable (0.8 m/s^2 – 1.25 m/s^2), very uncomfortable (1.25 m/s^2 – 2.0 m/s^2) and extremely uncomfortable (above 2 m/s^2). The experiment was conducted for a bus ride and the Budapest Rack Rail (BRR). For assessing riding comfort, the collected acceleration data were compared with the comfort levels. According to the results of this study, the vertical acceleration values of the bus ride were much lower than the BRR ride and categorised as fairly uncomfortable. On the other hand, riding on the BRR was categorised as uncomfortable due to the irregular pattern of the tracks.

Amador-Jimenez and Christopher (2016) compared the riding comfort of different modes of public transportation in different cities using smartphones for data collection. In this research, vibrations along three axes were examined and weighted using the ISO 2631-5 (2004) recommendations. For the case study, three different commuter trains in three different cities, including Montreal, Santo Domingo and London, were compared. According to the results, acceleration against Y shows smooth braking (deceleration) for the London Underground and the Santo Domingo train due to the use of appropriate braking systems. On the other hand, because of the use of an old braking system, the Montreal metro showed irregular patterns in this regard. Acceleration against Z in the London Underground showed that the ride is quiet and calm compared to the Montreal metro and the Santo Domingo metro due to better rail infrastructure and better damping. Acceleration against X showed similar patterns in the three trains and is not as important as other factors due to the large turning radii in railways.

Azzoug and Kaewunruen (2017) investigated the effect of acceleration on the discomfort of standing passengers on different public rail transport lines in the UK. For field study, a train shunter which only travels up to 27 km/h has been used. In order to achieve this objective, an Android-based smartphone equipped with an accelerometer was placed inside the vehicle at the end of the carriage along with a sophisticated accelerometer. In this experiment, to capture the acceleration data, an acceleration monitor application was used. Time and acceleration data were collected. Data analysis techniques were used to compare the accuracy of acceleration data collected by the phone and the accelerometer. Then the data was used to predict the passenger comfort or discomfort based on ISO 2631-1(1997) standard. Based on the findings of this study, accelerometers embedded in modern smartphones are more than enough to measure ride comfort data.

6. Drones

A drone or Unmanned Aerial Vehicle (UAV) is a small aircraft that can fly autonomously (or remotely controlled) and is able to capture rail defects such as deformed structure or missing parts (track and sleeper). They are working based on a pre-programmed path using complex intricate dynamic systems. Due to their simplicity of use and capability to gather useful information at an acceptable speed, drones are a potential tool for railway inspections today. An important benefit of using drones lies in the reduced time necessary for inspectors to be in the proximity of a railway line. Furthermore, in hazardous locations or areas where rail inspectors are at the risk of moving trains, using drones is helpful. Depending on the capacity of the batteries and the distance from the operator, the speed of drones can reach 30 km/h. Different types of sensors can be employed by drones, such as thermographic cameras and high-definition digital video cameras. The distance between a drone and the operator (pilot) ranges between 1 and 10 km (Páli et al. 2014; Kovacevic et al. 2016; Singh et al. 2018). Recently, LiDAR technology has been exploited by drones to collect useful data during aerial surveys. There are some limitations which must be considered regarding the use of drones, such as the high cost in the case of crashes and the inability to conduct railway inspections in all weather conditions (Kacunic & Car 2016).

Table 2 provides a summary and comparison of the above applications, together with their capabilities, inspection speed and their major limitations.

DISCUSSION

In this paper, different sensors for detecting railway defects have been discussed. A sensor might have some strengths and some weaknesses. Fault detection sensors can be compared with different criteria. Two main factors that can be considered to distinguish the capabilities of a sensor from others are firstly their potential to cover railway defects and the inspection speed. In terms of inspection speed, existing sensors such as mechanical sensors and MFL technique have limitations to inspect railway defects at high speeds. On the other hand, there are a number of sensors which can operate at a higher speed such as UT sensors and cameras. It must be mentioned that the higher speed does not always guarantee the acuracy of the inspection. As the pollutant, roughness, extra noise, darkness and environmental dirt can reduce their accuracy and efficiency.

In terms of defect coverage, conventional NDT sensors such as UT, EC and EMAT are reliable in detecting of surface and sub-surface rail defect but when inspecting the track geometry irregularities is raised then these techniques are not applicable. On the other hands, optical laser measurement sensors and advanced cameras can be used to detect both track irregularities and surface defects. But they are not useful for inspecting sub-surface rail defect. Recently accelerometers transducers are successfully applied in rail inspection in order to capture wide ranges of rail defects such as surface defects,

TABLE 2. Summary and comparison of inspection devices applied in railway inspection

Methods	Sensors	Type of defects	Preferred Inspection coverage	Inspection speed (km/h)	Major limitations
Wayside detectors	NDT sensors, Optic laser, accelerometers and high-speed digital camera	Wheel profile, cracks on the wheel, hot wheel bearing	Attached to the rail	Up to train speed	✓ Applicable to the only wheel and bearing components
Trolley	Basic NDT sensors, GPS, gyroscope, mechanical sensors	Internal and surface defects, track geometry irregularities	Small-scale inspection	30	✓ Lower speed ✓ Inspection without similar loading of normal trains
Hi-rail vehicles	NDT sensors, cameras, GPS, gyroscope	Internal and surface defects, wear and profile defects, track geometry irregularities	Medium-scale inspection	35	✓ Lower speed ✓ Inspection without similar loading of normal trains
TRV	Advanced NDT sensors, cameras, GPS, gyroscope, irregularities	Internal and surface defects, wear and profile defects, track geometry	Large-scale inspection	250	✓ Expensive for inspection ✓ Impose restrictions on traffic in case of using low-speed TRV
Vehicle-based CMS	Accelerometer, GPS, gyroscope	Surface defects, wear and profile defects, track geometry irregularities	No limitations	Up to train speed	✓ Few studies have been done ✓ Complexity in making links between different parts of the system (car-body CMS)
Smart-phones	Accelerometer, cameras, GPS, gyroscope	Surface defects, track track geometry irregularities	No limitations	Up to train speed	✓ Limited studies have been done ✓ Accuracy of these devices needs to be assessed
Drone	Cameras	Missing parts, surface defects	Small-scale inspection	Up to 30	✓ Limited studies have been done ✓ Maximum distance between drone and operator is 10 km2.

track irregularities and ride-comfort data. Acoustic sensors and thermal sensors are mostly applied in railway system for diagnosis of the problems related to rolling stock.

Respectively various inspection devices based on the mentioned sensors have been examined. These devices can be divided into wayside detectors and movable detectors. Wayside detectors are often applied to identify defects related to wheels, bogies and bearings. Movable detectors are mostly applied to detect rail defects and track irregularities. Applications of trolley and hi-rail vehicles are not costly but it must be taken into account that their capabilities to detect a wide range of defects are limited. TRVs are major and advanced means of rail track inspection. Although these vehicles are powerful for inspection, there are some drawbacks regarding their application. Firstly, the cost of using a TRV for inspecting a railway line compared to other devices is very high. Secondly, by using TRVs (lower speed), one track line can be assessed fewer times in a year because the railway line needs to be closed for train traffic. In contrast, CMSs, which can be equipped with different sensors, are more cost-effective and accessible. This type of detector is significantly cheaper than a TRV and can be carried by in-service vehicles without any disruptions to train services. Therefore, the track condition can be monitored several times a day.

Moreover, the application of smartphones in railway inspection has been discussed. Smartphones are pocket-sized condition monitoring devices which are provided with a variety of sensors and capabilities. Recently, they have been employed successfully for predicting passenger ride comfort based on rail track irregularities and rail surface defects. Smartphones are acessible, small and cost-effective devices which can be carried by onboard passengers. The major drawback of this type of application is that these devices as probes in railway inspection have not been fully developed. Lastly, the application of drones in railways was discussed. Investment in drones as new inspection devices is reasonable, as they can help rail operators to save time and monitor rail tracks for missing parts and surface defects especially at inaccessible areas.

CONCLUSIONS

With increasing population and consequently increasing demand for public transportation, rail networks around the world are becoming busier and faster. This issue can result in more axle loads and subsequently more pressure and stress on railway infrastructure. Regular inspection is the major prerequisite for implementing preventive maintenance, which can revitalise rail assets. In this research, various sensors and inspection devices for detecting rial defects and track irregularities have been examined and their specifications explained. Finding the correct parameters or faults that need to be measured is the most important factor for selecting the most appropriate inspection device, as each device has strengths and limitations. Investigating the different studies has shown that investment in deployment and development of cost-effective devices such as CMSs and portable devices such as smartphones can make the inspection of railway infrastructure more realistic and accessible.

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