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ORIGINAL RESEARCH

New methods and functionalities for railway maintenance through a draisine prototype based on RADAR sensors

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Abstract

Inspection of the railway tracks requires relying on a precise positioning system that accurately determines the location of potential failures and deficiencies. Therefore, measuring the speed and precise location of rail vehicles is essential. Many methods and approaches have been proposed, but most of them lack several conditions that do not allow them to be optimal for this task. In this paper, the authors present a novel method for measuring the speed of a train by means of the time correlation approach, by using 2-mm wave radar sensors. Additionally, it is also an accurate positioning system because the authors prove that the track has a unique profile, sufficiently characteristic and stable over time, that serves as a distinctive signature, which can be used to locate the vehicle at any point on that track. As a result, this new methodology, combined with a laser profilometer device, can be used as an effective inspection system for cracks or deficiencies in the rails, sleepers, fastenings, bolts etc., locating them precisely on the railway track.

1 | INTRODUCTION

Train operation control systems, including precise localization of rail vehicles, are a key element for many reasons related to security and efficiency, among others. For instance, to carry out the inspection of the railway track as effectively as possible, the maintenance service needs to rely on a precise positioning system that accurately determines the location of potential failures deficiencies.

1.1 | Positioning in inspection systems

Precise odometry is crucial for reducing the wayside equipment, which is expensive and requires maintenance. When train positioning is based on odometry, which suffers from cumulative errors, high precision is required. The simplest approach is the use of a tachometer. However, the slipping, the blockage and the variable radius of the wheel due to its conicity limit its precision [1].

Odometry can be also estimated based on instantaneous speed measurements. The typical approach for measuring the speed is the use of a radio Doppler sensor. Doppler effect measures the relative radial speed between two objects by detecting the change of the frequency of the signal that is transmitted by the first object (the train) and the second one (the sleeper) where the signal is reflected to the first object. To increase the reflected power, the Doppler sensor is tilted down with a known angle for pointing to the corner between the sleepers and the ballast. Unfortunately, this angle is variable due to an irregular surface and, typically, its accuracy is $\pm$ 1% error [2].

A different manner for measuring the speed is to use time correlation between sensors that are aligned according to the longitudinal axis of the tracks with a known gap between them. The main advantage of this technique is that speed error can be reduced to a certain value by increasing the gap between both sensors. Several methods have been explored with this approach. One of them is to induce currents in the track and measure the magnetic field that typically changes due to the presence of the rail clamps, the turnouts and the cables [3],

TABLE 1 Positioning systems and their disadvantages.

Positioning system	Disadvantages
GPS Odometry	Lack of coverage in underground stretches and low accuracy.
Taco-generators	Failure in case of traction skating or braking locking.
RADAR Doppler	Flat surface failure.
Monoaxial accelerometer	Need for continuous monitoring to determine speed and position.

but this method is not accurate enough at low speeds. Another method is to use optical sensors for measuring the irregularities of the surface of the tracks [4]. However, optical devices are not optimal for dirty environments and maintenance is required for cleaning. Finally, time correlation of two Doppler sensors has been proposed with limited results [5]. None of these solutions have been commercially exploited due to their lack of reliability and repeatability.

The implementation of MEMS (Micro Electro Mechanical Systems) technology in the sensors of the Inertial Motion Units (IMUs) has increased its sensibility. However, the calculation of distance and speed cannot rely on a single sensor because they depend on operating conditions (rain, snow, fog, hills, slipping etc.) and, thus, must be combined, for instance by means of fusion algorithms [6]. For instance, speed measurement is the result of the combination of wheel sensor, radar and Global Navigation Satellite System (GNSS). However, the GNSS receiver should be able to autonomously perform integrity monitoring, including detection of faulty observations [7].

Therefore, the IMUS have been used for supporting GNSS receivers in the areas where they do not have availability. An example is based on onboard sensors such as a velocity sensor and a GNSS sensor [8]. The other examples are based on particle filters that fuse the position and direction observations to estimate the vehicle position [9]. However, this approach has had a limited commercial success [10], mainly because of the absence of satellite signals in places that are important for railroad applications (railway stations, tunnels etc.) [11]. Additionally, increasing the number of onboard sensors is cost intensive and only gradually improves reliability and availability of localization information [11].

Table 1 summarizes the positioning systems currently used in the railway environment, along with their main drawbacks.

Within this context, the authors of this work, who belong to Auto Drive Solutions (ADS), have developed a new positioning system based on millimeter-wave (mm-wave) RADAR sensors that tries to solve all the disadvantages that current systems have. Its function is based on previous works already registered by ADS [12]. In this paper, we present a novel method for measuring the speed of the train by means of the time correlation approach, by using 2-mm wave radar sensors. We have based our methodology on the precise and continuous extent of the profile of the railway track, acquired by means of radar sensors. The purpose of using mm-wave radars is to obtain an infrastructure signature that is sufficiently characteristic and stable over time to allow the speed and position of the train to be determined with a precision never seen before

In this way, each one of the disadvantages shown in Table 1 is solved as follows:

- Lack of coverage in underground sections and low accuracy: There is no lack of coverage because the positioning system is embarked on the vehicle itself that is performing the inspection of the railway track.
- Failure in case of traction skating or braking locking: Since, in these cases, the vehicle continues to move, the on-board measuring equipment continues to move equally and is not influenced by this fact.
- Flat surface failure. Flat surfaces are not a problem for this system. The result will be a measurement of a ‘flat’ profile. The precision of the developed system is able to measure distances of less than 1 mm, so a flat surface for the human eye is not really flat for this positioning system.
- Need for continuous monitoring to determine speed. Our positioning system continuously calculates the absolute position of the vehicle within the entire railway track. Therefore, continuous monitoring is not necessary.

1.2 | Aims and structure of the paper

The main objective of this project is to verify, by means of a set of tests designed and customized to such an effect, that the use of mm-wave RADAR sensors (which had never been used previously for this purpose) is suitable for their application to railway operation and maintenance. In particular, the specific objective of this work is to verify the adequacy of the performances of a new prototype:

- mm-wave RADAR sensors can be used as an accurate positioning system because the track has a unique profile that serves as a distinctive signature, which can be used to locate the vehicle at any point of that track.
- RADAR systems can be used as a precise speedometer, by comparison of the profile of the track recorded by two consecutive sensors.
- They can be used as an effective inspection system of cracks or deficiencies in the railway track and to locate them precisely on the track.

The structure of this paper is as follows: previous work in the field is briefly reported in the following paragraphs of this section. Then, Section 2 introduces the operative of the new system, including the methodology for the positioning, speed measuring and inspection of the railway track with the different sensors. The described methodology is applied for performing the four experimental tests presented on Section 4. The paper closes in Section 5 with the main conclusions and some indications for plans about future work in the field.

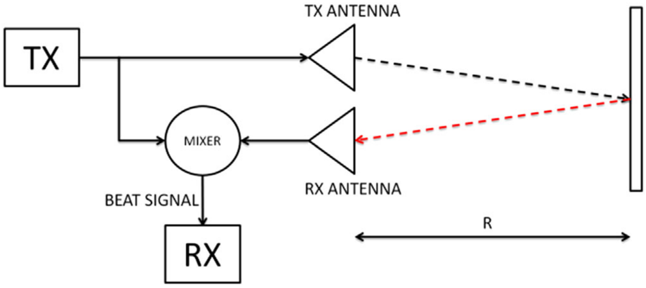


FIGURE 1 Architecture of a FMCW radar. FMCW, frequency modulation continuous-wave.

2 | OPERATIVE OF THE NEW SYSTEM

2.1 | Functioning of mm-wave radars and ground-profile correlation

A radar is a system that uses electromagnetic radiation reflected by an object to determine the location or speed of the object. In practice, a radar system may be able to measure direction, height, distance, heading or speed from the echo reflected by both static and mobile objects.

Due to a high cost of components, the use of mm-wave sensors has been typically limited to space exploration and security applications [13–16]. In recent years, technological advances in radio frequency have given rise to new Silicon-Germanium components in the millimetre band [30–300 GHz]. An example of this is the low-cost frequency modulation continuous-wave (FMCW) radar [17], which works in the 120- to 125-GHz band and most of its components, including also a transmitter and receiver antennas, are embedded in a single chip.

It is worth noting that mm-wave radar sensors have many advantages in comparison with optical sensors, since the radar signal is reflected over any type of surface even on those that present a low retro-reflectivity or are covered by sand or dust. Furthermore, radar reliability does not depend on light conditions and works well under heavy rain or fog conditions. These properties make mm-wave radars ideal for non-clean outdoor environments.

The working principle of a FMCW radar consists in transmitting a chirp signal (a signal that changes its frequency along the time) and measuring the time of flight that this signal takes to bounce on the target and returns to the sensor. Figure 1 shows the architecture of a FMCW radar.

Figure 2 shows a saw tooth radar waveform with linear frequency modulation. The returned signal (dotted red trace) is mixed with a copy of the transmitted signal (continuous black trace). As a result of mixing both signals, we obtain another signal, called beat signal, whose frequency is proportional to the distance to the target. The frequency of the beat signal is determined by Equation (1) where R is the distance to the target, c is the speed of light in the medium, Δf is the total transmitted bandwidth and T is the period of the chirp signal.

$$f_{beat} = \frac{2R}{c}\frac{\Delta f}{T}\ (Hz) \tag{1}$$

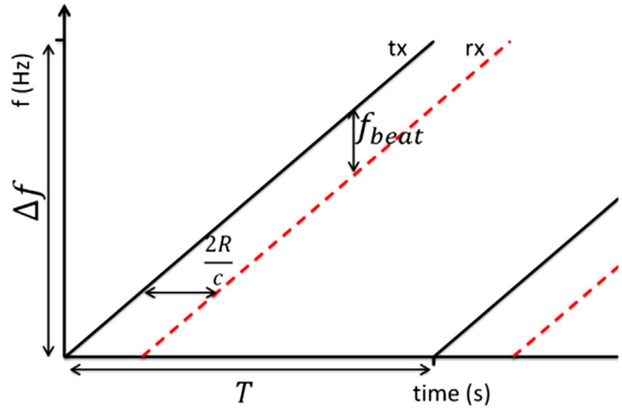


FIGURE 2 Graph of the saw-tooth radar waveform.

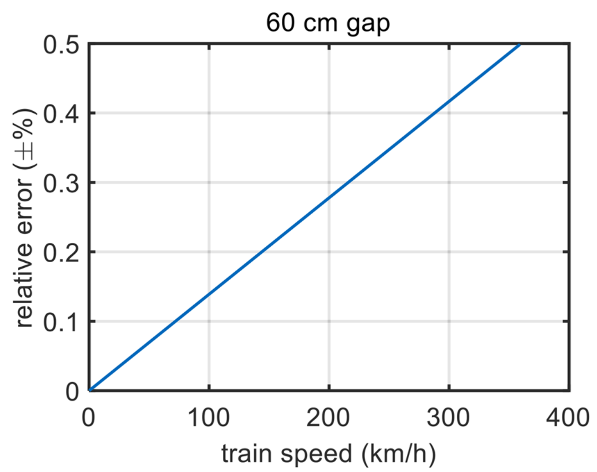


FIGURE 3 Theoretical relative speed error for a 60-cm gap between sensors.

The theoretical cross-correlation error should be ± 1 sample; the number of samples where the correlation will find the maximum will be the time that second radar (A) takes to reach the initial position of the first radar (B) divided by the period T. This value will depend on the gap between radars and the speed of the train. Equation (2) shows the theoretical error where $t_{measured}$ is the delayed obtained in the cross-correlation, T_{chirp} is the scanning time of one measurement of range, Gap is the distance between sensors and V_{train} is the real speed of the train.

$$\varepsilon_{speed} = \frac{t_{measured}}{\frac{Gap}{V_{train}}} = \frac{\frac{Gap}{V_{train}} \pm T_{chirp}}{\frac{Gap}{V_{train}}} = 1 \pm \frac{V_{train} * T_{chirp}}{Gap}\ (adim) \tag{2}$$

Figure 3 shows the function of the theoretical speed estimation relative error versus train speed for a 60-cm gap. This error is typically about 10 times better than the error of current systems for determining train speed. However, it can be reduced up to 600 times by placing the first sensor at the head of a 400-m train and the second sensor in the tail.

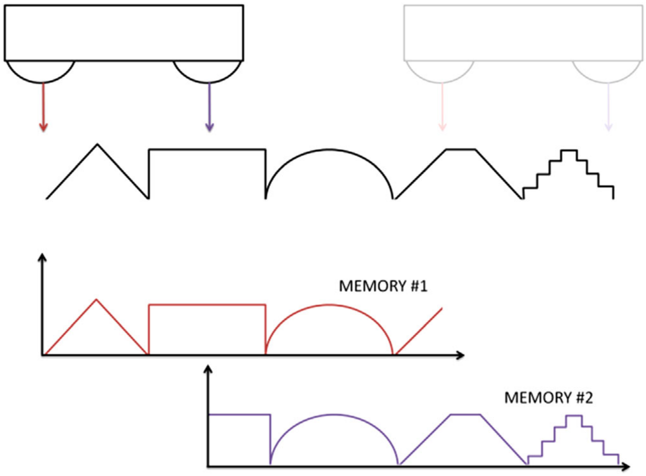


FIGURE 4 Example of a schematic profile of the railway track.

2.2 | Operative of the positioning system

Once the need for an accurate positioning system to increase the efficiency of rail maintenance systems has been defined, this section will describe the operative of the positioning system used in this work.

In short, the system is based on the following assumption: the railway track has a unique signature at every point, a surface identity, determined by surface characteristics like irregularities or inaccuracies depending on construction systems or maintenance. Based on this premise, the reading of the railway track in a given section results in a surface identity profile that allows defining precisely the positioning of the vehicle that carries the measurement system. It is important to distinguish this surface track profile that we will take into consideration to the infrastructure profile defined by the elevation of the different mileage point along the alignment.

Let us suppose that, schematically, the entire railway track had a profile like Figure 4, where the triangle rectangle and the circle represent different patterns found on the railway track (e.g. sleepers, bolts, ballast, clips etc.).

Moreover, let us suppose that the profile of the last leg measured by the positioning system has had a rectangular shape. Conceptually, it would have been easily determined that the vehicle was in the middle of the railway track.

However, although the operation of the developed positioning system may seem simple, it must meet two requirements to make it effective. The first one is that the profile measurement is extremely accurate, and the second one is that it is extremely fast.

On the one hand, it has to be extremely precise because the characteristics that will determine the uniqueness of the railway track signature are small, for example, the centimetre difference in separation between several consecutive sleepers, the uniqueness of the ballast shape, or the average distance between the vehicle and the sleeper in a given section.

On the other hand, it has to be extremely fast because the inspection of the railway track could be done at any speed.

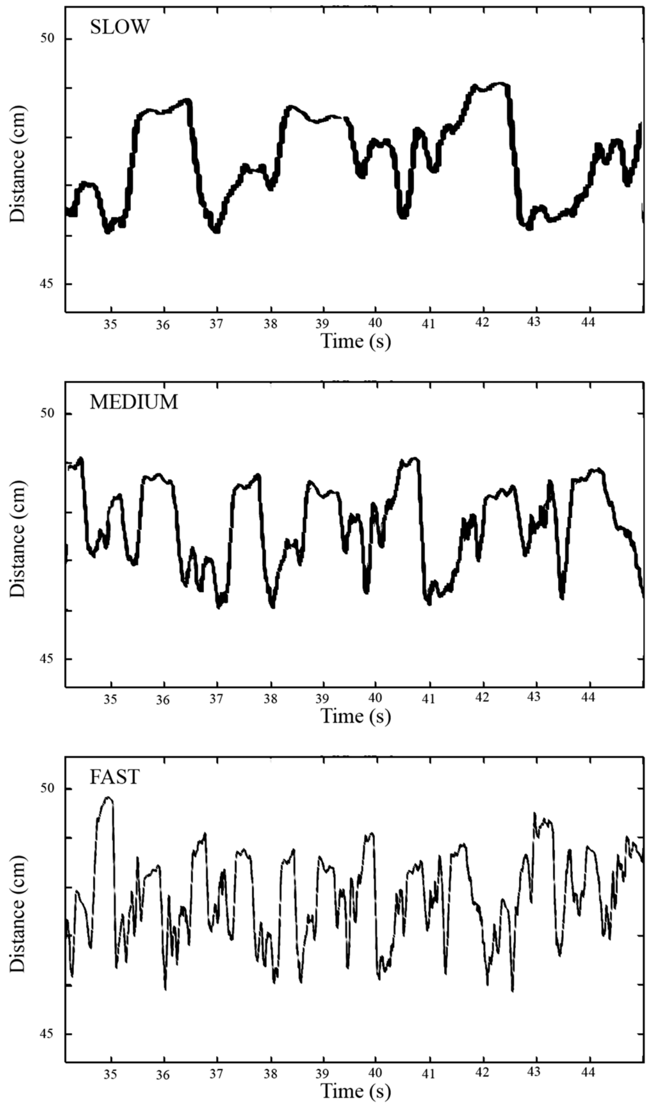


FIGURE 5 Readings of three equal track profiles at different speeds: Slow (above), Medium (middle) and Fast (below).

This, coupled with the first requirement, obliges that the profile measurement has to be 'almost' continuous.

In addition, the fact that the speed of inspection of the railway track is variable requires that the profile reading system must know constantly the speed of the vehicle to be able to perform an accurate positioning. For example, Figure 5 shows the schematic readings of three equal profiles, but at different speeds.

Therefore, it is necessary to correct the measured profile with speed information to determine with accuracy the exact position of a vehicle within the entire railway track. Thus, the procedure that summarizes the operation of the complete positioning system would be as the following steps:

1) Measurement and storage of the full profile of the railway track and the speed at which it was made.
2) Normalization and storage of the normalized full profile at a certain rate (normalization rate) of the measured profile.

FIGURE 6 Radar sensor that has been developed to read the railway track profile.

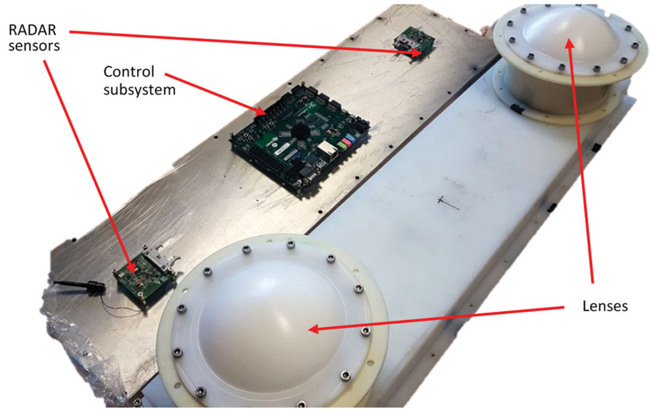


FIGURE 7 Prototype of the speedometer with the coupled sensors.

3) Measurement of a partial profile of a small section (2–5 m) of the railway track.
4) Normalization of the partial profile of that section with respect to the normalized full profile.
5) Determining the positioning of the vehicle within the full profile stored in Step 2.
6) Update of the measured segment of the full profile in the event of any significant changes in the partial profile.
7) Repeat Steps 3 to 6 continuously to position the vehicle.

Following these requirements, Figure 6 shows the radar sensor that has been developed by the authors of this work, belonging to ADS, to read the railway track profile.

As explained before, a radar transmits a signal that periodically changes in frequency and then it receives the echoes that, correctly treated, will provide us with information about the irradiated object. If the focus takes the right direction, that is, if any object has been irradiated with the signal emitted by the radar, a reproduction of the transmitted signal will be collected at the receiver, but with lower power and temporarily delayed. This delay from the transmitted signal is equivalent to twice the distance to the irradiated object.

The sensor that we have designed is a mm-wave radar device that operates at a central frequency of 120 and 18 GHz bandwidth. Such a device is capable of measuring the distance to a target at a frequency of 10 kHz (10,000 times per second) and with an accuracy of 100 μm. Therefore, it is the ideal technology to meet the requirements previously presented for accuracy and speed.

2.3 | Operative of the speedometer prototype

As noted above, to accurately perform the positioning of the vehicle, the instantaneous speed information is required. Our positioning system can also be used as a speedometer to determine with high accuracy (less than 1% error) the instantaneous speed of the vehicle.

The operational philosophy of our speedometer follows a similar premise to the one of the positioning system: the railway track has a unique signature at every point determined by surface irregularities or inaccuracies in construction systems.

Our speedometer is based on the use of two radar sensors as those exposed in the previous section. They are separated at a fixed distance of 60 cm along the vehicle's axis of motion. In this way, the speed is determined by the time that elapses since the moment that the first sensor reads a feature of the railway track, until the second sensor reads the same feature.

Apart from assessing the speed of the vehicle, this double disposition of sensors provides an additional objective: obtaining redundant information that makes the positioning system more robust.

Considering this design, the prototype of the speedometer with the coupled sensors that has been built and will be tested is presented in Figure 7. As can be seen in the image, each of the two sensors has a lens whose function is to focus the power transmitted by the radar in a 1-cm diameter at a distance from the lens between 20 and 70 cm. These characteristics have been designed in this way by taking into account the great irregularity of the railway track, in such a way that it gives the system great versatility to be installed in various inspection vehicles without limiting the design of the system to any parameter dependent on them.

Internally, the system consists of the two sensors located under each of the lenses, with the control subsystem between them. The latter is responsible for the processing of the measurements, the determination of the position and speed of the vehicle and the communication of the system with the inspection vehicle.

The global procedure of this new methodology is as follows:

- Firstly, the speed of the train is determined by comparing two profiles of the infrastructure obtained by means of two radars arranged longitudinally. These profiles must be identical except for the delay caused by the separation between sensors.
- Once the speed of the train is determined, it is possible to store the normalized profile at a given speed.
- This normalized profile is loaded into the train's memory.
- The next time the train travels on the track, its speed will be determined for normalizing the last 100 m travelled to the set

speed. Then, a correlation will be made of said 100-m profile with the profile stored in memory.
- The correlation will produce a maximum at the point where the train is located, so it will be possible to determine precisely its position.

The accuracy of the speed estimation is not degraded when signal noises are present in one or either sensors, or when the ground profiles of both sensors are slightly different. For example, this potential mismatch between profiles would happen in snowed surfaces. In this case, the effect of the wind, while the train passes through, could change slightly the shape of the snowed surface and this fact would impact the correlation with a lower height of the relative maximum. However, the position of the peak that is associated with the speed of the train will not change, especially if the correlation is made with the last scanned 100 m of infrastructure. Cross correlation of both radars would obtain a wrong speed estimation only if one of the sensors is measuring an identical profile of the other sensor with a constant delay.

2.4 | Operative of the railway track inspection

The objective of the inspection of the railway superstructure is monitoring all the elements that make up the track, thus determining the condition, wear, cracking or breakage thereof. In addition, this inspection should also be able to determine the status of the fasteners, clips, nuts and bolts deployed on the track in order to detect the state in which they are kept and thus report to the maintenance system the need for preventive repair.

We opted for the use of two different systems to perform the inspection of the superstructure, which will be exposed below. The first one is a commercial device based on a laser profilometer commonly used for inspecting production lines and the second one uses our own technology based on the radar sensor presented above.

2.4.1 | Inspection with laser device

The laser device is the profile sensor Gocator 2170, developed by LMI Technologies, whose features are shown in Figure 8.

2.4.2 | Inspection with radar sensor

The operating principle used for the detection of visible defaults in the rail of the railway track is the same as the proposed for the positioning system and speedometer, based on our radar sensor. Initially, the system will be used for rail break detection.

The equipment used for this purpose will be the same as described in the previous section, with the exception of its position on the track and the inspection vehicle. If for the speedometer the position of the equipment was parallel to the tracks, in this case, the disposition of the device will be perpendicular to railway, placing one of the two sensors illuminating exactly the centre of the rail as can be seen in Figure 9.

Thus, in the case of the rail inspection system, sensor 1 is responsible for detecting possible rail failures, while sensor 2 is responsible for positioning the vehicle, and therefore positioning the exact location of railway track problems. The speed information at each point is still required in order to normalize the measured profile of the railway track. However, at this early design stage, this measurement will be given by an external device connected to the vehicle. This device is a standard diagnostic tool that uses the port On Board Diagnostics-II (OBD-II) of vehicles to extract the current vehicle information. In any case, it is easily deducted that with three radar sensors disposed on L-shape it will be possible to carry out the three required functions.

In conclusion, the new system that has been developed for the maintenance of railway track is a fully versatile system capable of carrying out positioning, speed measurement and inspection tasks simultaneously.

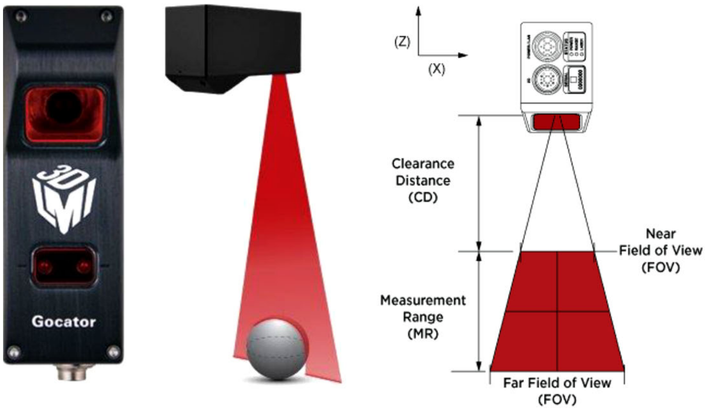
3 | TESTS

Tests have been carried out on two different railway tracks: one of them was a UIC-45 rails and wooden sleepers with a high degree of deterioration and poor maintenance of rails, sleepers, fasteners and clips (railway track 1); the other one consisted of a newly built railway with monoblock concrete sleepers and in good condition (railway track 2). The results of each of them are therefore presented individually in this section for subsequently determining the conclusions on a comprehensive basis.

3.1 | Equipment and tools for the tests

For the realization of all the tests the materials used were

- Draisine. Toyota Hilux vehicle, modified to be a bi-rail vehicle capable of performing railway track inspection.
- Prototype of positioning system and speedometer developed by ADSs.
- Own software developed by ADSs for real-time visualization of measurements.
- Frame or clamping trolley. This element is responsible for attaching the equipment to the structure of the draisine in order to avoid vibrations and fix the equipment.
- OBD-II device. Diagnostic tool that uses the standard port of vehicles to read the instantaneous speed of the draisine at all times.
- Laser profilometer Gocator 2710 from LMI Technologies.
- 12-V power wire connected to the vehicle battery to power all electronic equipment.
- Ethernet cable for communication and storage of measurement data.
- Inverter from 12 V DC to 230 V AC to power electronic equipment with home network power.



Measuring range	500 mm
Clearance distance	400 mm
Field of view (near-far)	308-687 mm
Z Resolution	0.055 mm
Resolution X	0.55 mm

FIGURE 8 Photo, functioning scheme and features of profile sensor Gocator 2170.

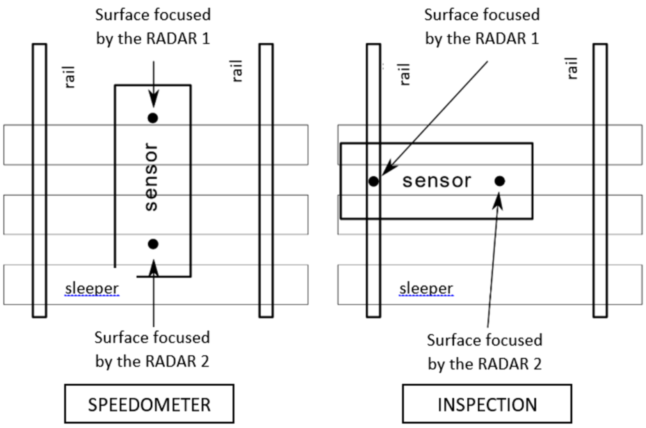


FIGURE 9 Disposition of sensors 1 and 2 for the speedometer (left) and for the inspection (right).

- PC for communication with the measurement system. Toshiba Satellite Pro P500-11Z.
- Wireshark software for storing all measurement data.
- Helmets, vests and safety boots.

Figure 10 shows the graphical interface developed to read the data generated by the measurement equipment. This software allows it to read the data, start testing or annotate it in real time in order to process it as shown in the Results section of this document.

3.2 | Characteristics of the railway tracks for the tests

Table 2 presents and compares the characteristics of the two different railway tracks used for performing the tests of the present study.

3.3 | Matrix of test design

Table 3 represents a matrix for understanding the different tests carried out in this study. As can be seen, it classifies the experiments depending on the railway track on which they have been performed, the equipment used and the validation of results that have been sought for each one. Related to the radar sensors, it establishes if both of them were aligned parallel (=) or perpendicular (+) to the railway track.

3.4 | Test 1 on railway track 1

3.4.1 | Assembling of the equipment

This section explains how was the assembly of both equipment in the vehicle modified as a draisine during the tests for positioning and speed measurement: the radar sensors and the laser device.

On the one hand, Figure 13 shows the prototype of radar sensors, which is located in a frame anchored at the back of the draisine, parallel to the rails of the railway track at approximately 40 cm above the floor. This distance is within the focus (20–70 cm) for which the sensor lens has been designed. In this way, the two sensors of the equipment will read exactly the same points of the railway track and, as explained previously, will determine both the positioning and the speed of the vehicle.

On the other hand, Figure 14 shows the location of the laser profilometer for the inspection of the track elements. As can be seen, the placement of this additional equipment did not cause any problems or interference for the measurements of the speedometer developed by ADS.

3.4.2 | Tests design

The tests that have been carried out are mainly divided into two different blocks, according to the two configurations that have been proposed

- Positioning system and speed measurement by means of the radar sensors and inspection of the track by means of the laser profilometer.

FIGURE 10 Graphical interface of the software developed to read the data from the measurement equipment.

TABLE 2 Characteristics of the two railway tracks for the tests.

	Railway track 1	Railway track 2
Type of track	On ballast	On ballast
Width	Iberian width (1668 mm)	Iberian width (1668 mm)
Approx. length	1 km	10 km
Placement	Outdoors	Outdoors
Sleeper material	Wooden	Concrete
Track clamping	Directly on the sleepers	With clips
Approx. sleeper separation	40 cm	40 cm
Approx. sleeper width	20 cm	20 cm
State of conservation	Poor	Good
Maintenance	Poor	Low (some areas full of ballast)
Appearance	Figure 11	Figure 12

FIGURE 11 (Left) Image of the railway of railway track 1.

- Tests carried out:
  - Fifteen repetitions in a single direction of the track with the two sensors positioned parallel to the rails.
- Objectives:
  - Corroborate that the railway track has a unique signature
  - Complete characterization of the track
  - Test and calibrate of the speedometer prototype
  - Test and calibrate of the positioning system
  - Detect damages on the sleepers.
  - Detect abnormal elements on the track
- Acquired data:
  - Profile of the track recorded by the two radar sensors reading the same points
  - Vehicle speed with OBD-II to calibrate speedometer prototype.
- Expected results:
  - Storage of the standardized stretch of track profile
  - Comparison of the 15 repetitions of the entire stretch
  - Individual characterization of each sleeper.

TABLE 3 Matrix presenting the different tests carried out in this study.

		Equipment			Results and validation		
No. test	Railway track	Radar sensors	Laser device	OBD-II	Positioning	Speedometer	Inspection
1	1	=		x	x	x	x
2	1	+			x		x
3	2	=	x	x	x		x
4	1	=	x	x			x

OBD-II, on board diagnostics-II.

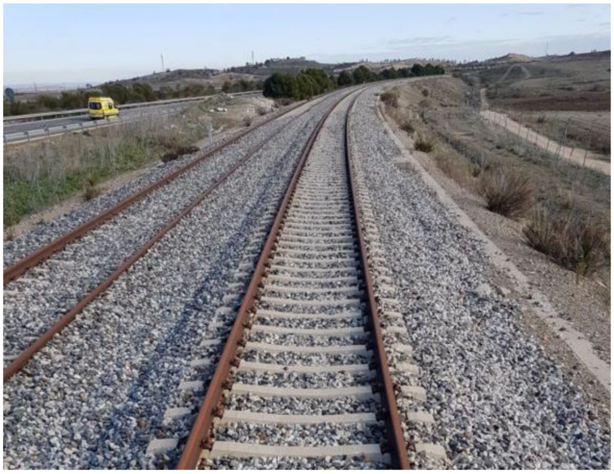


FIGURE 12 (Right) Image of the railway of railway track 2.

FIGURE 13 (Left) Assembling of the equipment for developing test 1 on railway track 1.

- Speed accuracy of the prototype with respect to OBD-II

3.4.3 | Test results

According to the two types of tests defined, the presentation of the result will follow the same structure (first position system and then speedometer); in this way, the results of the tests performed are as follows:

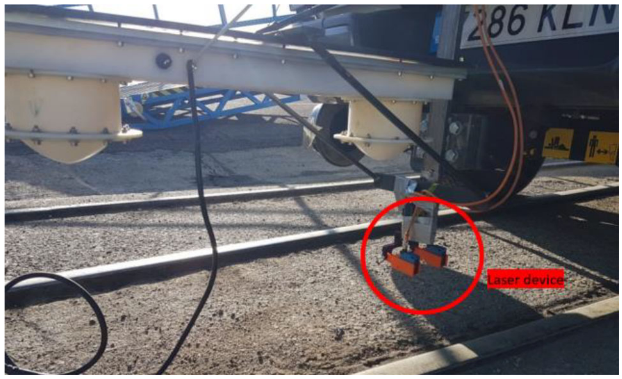


FIGURE 14 (Right) Location of the laser profilometer at the draisine.

- Characterization of the positioning system:

Figure 15 is just an example of the 15 couples of track profiles (see all of them in Appendix 3) that summarize the measurement of the profiles of the reading tests performed in the railway track 1. Each couple consists of the profiles recorded by the two radar sensors. The average duration of each recording is 1 min and each sensor performs one measurement every 100 µs. Therefore, the total amount of data acquired is 18 million measurements.

Even though the amount of data can seem overwhelming, two quick conclusions can be drawn at first sight

- The profiles of the two channels are very similar in each of the individual recordings.
- All profiles are very similar and it is possible to determine matches with the naked eye.

These two statements allow us to validate the initial hypothesis on which the positioning system is based: the railway track has a unique profile that gives it a unique signature, which allows it to position an element in the railway track with just a measure of the track profile.

To define it more precisely, let us zoom to a random area of the track profile. Let us take, for example, the profile segment from the second 34 of test No. 15 and profile of radar sensor 1 (Figure 16). At first glance, it is possible to determine at the profile where there is a sleeper and where there is ballast, as is pointed out in the graph.

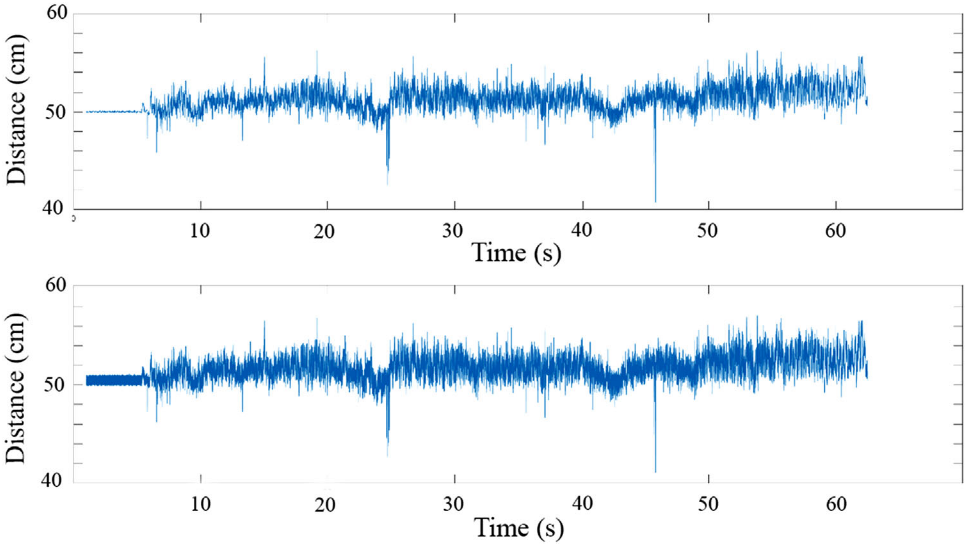


FIGURE 15 Track profiles recorded by each one the two radar sensors in each one of the 15 readings (see all of them in Appendix 3).

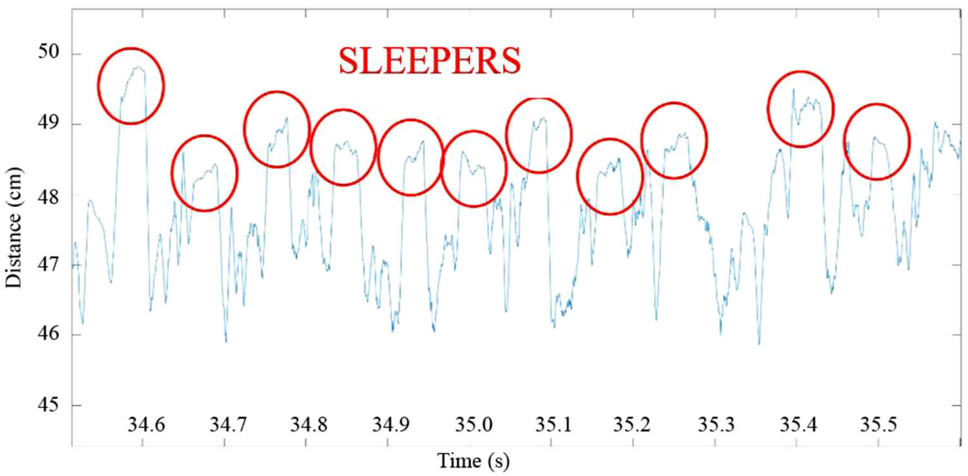


FIGURE 16 Zoom to segment of second 34 of test 15 and radar sensor 1.

As can be appreciated, each sleeper is totally different and independent of the adjoining sleeper, just as the ballast is at different heights and has a layout that may seem random. However, the graphic is clear enough to provide very useful information.

To characterize the railway track exhaustively, we have carried out a data processing of all the tests to characterize each sleeper individually and we have tabulated it. All this information is attached in Appendix 1 in a table with the following format or fields (first row in English, second row in Spanish):

- Index. It is the index of each sleeper within the stretch of railway track under study.
- Approximate PK. It is the approximate kilometre point of each sleeper. It is calculated taking on average the distance of two sleepers on the 0.6-m track.
- OBD-II speed. It is the average speed at which the vehicle was moving when it passed over that sleeper, determined by the OBD-II device.
- RPS speed. It is the average speed at which the vehicle moved when it passed over that sleeper, determined by our prototype of speedometer.
- Norm. profile. It is the average normalized profile of the sleeper with respect to the speed difference between the normalization speed (20 km/h) and the speed at which the draisine circulated at the time of each measurement.
- Height. It is the average height of the sleeper measure.
- Std. height. It is the typical deviation of the measurement of the height of the sleeper taking as data the values of the 15 tests and the two channels (one per radar sensor).
- Width. It is the average width of the sleeper measure.

TABLE 4 Statistical results on the sleepers of railway track 1.

No. of sleepers	Average height	Standard deviation in height	Average width	Standard deviation in width	Track condition (0–3)
1432	41.22 cm	5.24 cm	24.12 cm	2.38 cm	1.2

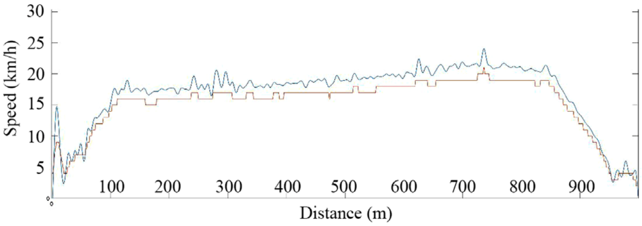


FIGURE 17 Graph comparing speeds taken with the OBD-II (red line) and the speedometer prototype (blue line) (see the 15 recordings in Appendix 4). OBD-II, on board diagnostics-II.

- Std. width. It is the typical deviation of the measurement of the width of the sleeper taking as data the values of the 15 tests and the two channels (one per radar sensor).
- State. Depending on the measured profile of each sleeper, we determine that the sleeper in in good, average, bad or very bad condition. These thresholds are based on the statistical data of mean and variance of measurements on the profile of the sleepers. When the variance is above 10%, 15% or 20% of the width of the sleeper, the state is defined respectively as average, bad or very bad. The results are weighted with the difference to the averages of the five previous and subsequent sleepers. Thus, this classification can be considered a first approach to a system for the inspection and maintenance of any railway track.

Taking into account all the information in the table of Appendix 1, Table 4 shows the most relevant statistical results.

As indicated in the section related to the characteristics of the railway track, the maintenance conditions of this railway are quite poor, having sleepers with important damages. Table 4 can prove this fact by means of the standard deviations, which will be confirmed in the images included in the following sections.

- Characterization of the speedometer accuracy

Figure 17 exposes just one of the 15 graphs showing the results of the speed measurements (see all of them in Appendix 4). These graphs compare the measurements obtained by our prototype of speedometer (blue line) with the diagnostic tool that uses the OBD-II standard of the draisine (red line).

In short, all speed curves in all 15 tests exhibit similar behaviour. The initial acceleration is quite smooth until the maximum speed (between 30–40 km/h) is reached. The only exception is the first test, in which the maximum speed was around 20 km/h to inspect the track for safety reasons.

The first conclusion that can be drawn is that our prototype of speedometer, which uses the railway track profile, is able to achieve an accuracy of 0.01 km/h, while the OBD-II system has an accuracy of only 1 km/h. In addition, the OBD-II system offers a lower measurement of speed than our speedometer. This may be due to two reasons:

I. the frequency of the OBD-II system (1 measure every 0.5 s) is much lower than the system under study (1 measured every 0.01 s), so the measurement in the first case is filtered and compensated, which does not happen in the second case;
II. the international regulations require vehicle speedometers to reduce the actual speed values for safety reasons; therefore, it is an induced error, mandatory and legal, established by the international legal institutions.

According to the results, our prototype of speedometer has presented low resolution at low speeds (under 5 km/h). This is because the profile size that is used for speed calculation is not sufficient at these speeds. It is an amendable error that will be corrected in subsequent field tests.

Finally, we detected that some of the errors in the measurement of the vehicle's speed are the result of the loose anchorage system that was used, which generates undesirable vibrations. Being the measurement of speed a system based on the comparison of profiles with some delay, the elimination of any type of vibration is fundamental and affects the measurement and the resulting values of speed. For correcting this problem, the following tests were developed after the construction of a new damped system that would promote the increased accuracy of the speedometer and positioning system as a whole.

3.5 | Test 2 on railway track 1

This time, the aim of the test was focused on the inspection system, using both the radar sensors and the laser device. The assembling of the equipment was similar to test 1, but the radar sensors were placed perpendicular to the railway track: one of the sensors was placed over the sleepers and the other one placed over the rail.

3.5.1 | Tests design

The tests that have been carried out are the following:

- Positioning system and inspection of the rail only by means of the radar sensors.
  - Tests carried out:

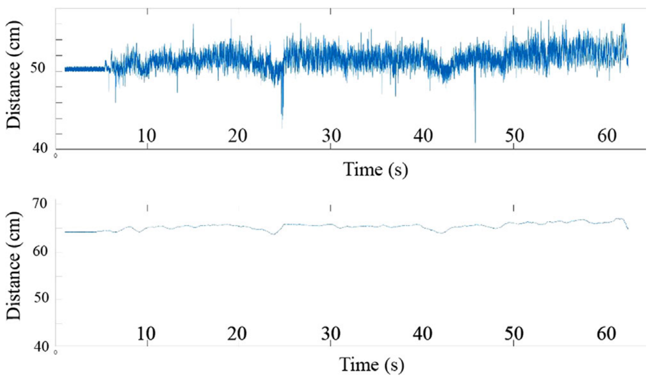


FIGURE 18 Reading for the inspection of the railway track 1 (track above, rail below) with the radar sensors (see all of them in Appendix 5).

   - Five repetitions in each direction of the track (10 in total), with one of the sensors placed over the sleepers and the other one placed over the rail.
- Objectives:
   - Detect rail damage.
   - Use the positioning system in conjunction with the inspection system.
- Acquired data:
   - Profile of the track by one radar sensor (for positioning system).
   - Profile of the rail by the other radar sensor (for rail inspection).
   - Profile of the track recorded by the laser device (failed)
   - Vehicle speed with OBD-II to normalize measurements of the profiles.
- Expected results:
   - Detection of possible damages in the rail and their exact position.
   - Determination of the severity of each damage by assessing the measurements.

3.5.2 | Test results

The results of the tests performed are as follows:

- Railway track inspection with the laser device

Related to the laser device, unfortunately, it did not deliver satisfactory results due to the light conditions of the tests. The results thereof will not be set out in the Results section of this work.

- Railway track inspection with the radar sensors

Figure 18 shows one of the 10 couples of graphs obtained in this test. All of them are exposed in Appendix 5, where the first five tests correspond to the inspection of the left rail and the last five to right rail. In Figure 18, the upper image shows the track profile (over the sleepers, at the centre of the railway) and the lower image shows the rail profile. They can be used to summarize the results of the tests performed to characterize the rail inspection system along with its use as a positioning system.

The main conclusions that can be drawn based on the results of the graphs above are

- As expected, the measurements of radar sensor 2, which performs the rail profile, are much more stable than the measurement of radar sensor 1 over the track, with sleeper and ballast. There is hardly a variation of 2 cm in the measurements of sensor 2 and they are largely due to the vibrations of the fixing structure.
- It can be seen that the duration of the first five repetitions is shorter (around 60 s) than those of the last five tests. This is because the last five tests to measure the right rail had to be performed driving reverse the draisine due to safety reasons.
- It can be determined at first sight that there appear to be several areas with out-of-average measurements; this study will try to demonstrate whether they can be characterized as problems in the rail.

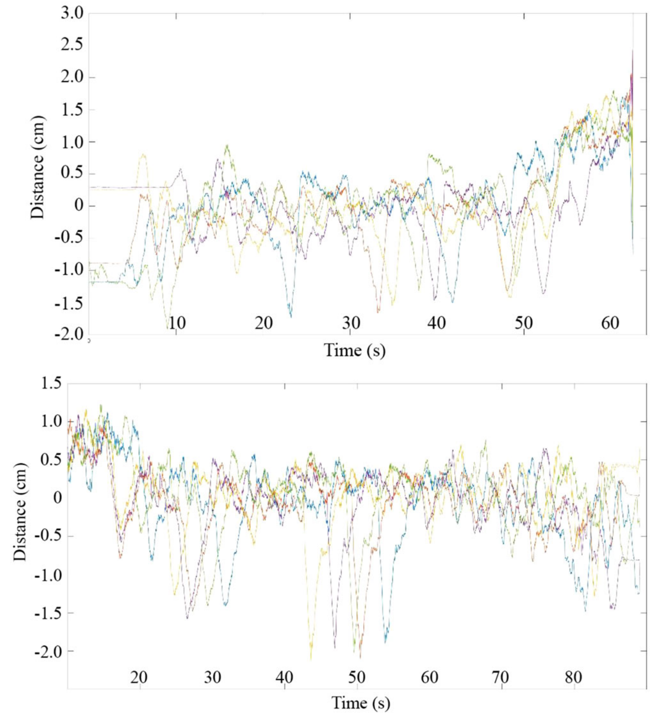


FIGURE 19 Rail profiles overlapped (left rail above and right rail below).

Figure 19 is used to appreciate all the rail profiles overlapped (left rail and right rail) to determine if the imperfections that are going to be analyzed are repeated coherently and, therefore, are not false positives.

Table 5 shows the problems encountered throughout railway track 1.

After performing a visual examination on positions that the inspection system had considered to be problematic, it is determined that the problem at the three points detected is the discontinuity of the rail because their junctions are not welded (Figure 20). Therefore, this is not a railway track failure.

FIGURE 20 Rail with flange joint without welding, confirmed during visual inspection.

FIGURE 21 Assembling of the equipment for developing the test 3 on railway track 2.

TABLE 5 Problems found in railway track 1 during test 2.

No.	Repetitions	Approx. location (m)	Severity	Visual inspection
1	5	212	Medium	Flange joint without welding
2	4	521	High	Flange joint without welding
3	5	951	Medium	Flange joint without welding

3.6 | Test 3 on railway track 2

3.6.1 | Assembling of the equipment

As explained in the previous section, we had found that the measurements on the tests on railway track 1 had a low-frequency error component due to vibrations produced by the anchorage system. To avoid these vibrations, we designed and manufactured a new anchorage system for the tests on railway track 2, which allows it positioning the sensor supported on the track over a trolley with two nylon wheels (Figure 21). This system offers greater stability against vibrations than the previous anchoring device, in which the vibrations were fought by cable tensioners.

As for the laser-based inspection system, since light conditions are extremely important for its proper operation, we also design a new covering structure that allows it to generate a shadow zone over the area of interest. Being this the case, it is possible to perform a correct inspection of the railway track, in this case over the rail. Figure 22 shows the placement of the laser device under the covering structure and the laser beam it emits to perform the corresponding measurement of the profile.

3.6.2 | Tests design

In this case, as railway track 2 is longer than railway track 1 (10 km vs. 1 km), the number of repetitions has been reduced to two. Since the radar sensor is less versatile than the laser profilometer when performing track inspection (it is only useful for inspecting sleeper or rail discontinuities), it was decided to use only the laser device as the inspection sensor, using the radar-based prototype as a positioning system and speedometer. Therefore, the two devices performed measurements simultaneously.

In this way, tests such as positioning system, speedometer and railway track inspection method consisted of:

- Tests carried out:

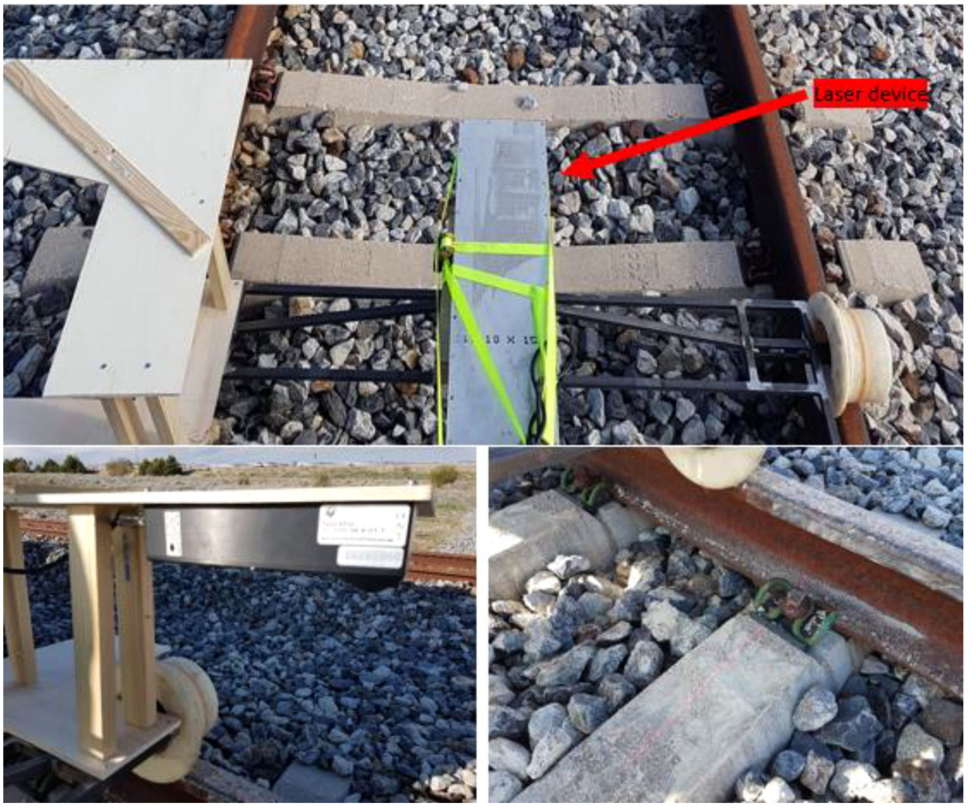


FIGURE 22 Assembling placement of the laser device and laser beam it emits (right down image).

- Two repetitions in a single direction on the track with the two sensors positioned parallel to the rails.
- Objectives
  - Corroborate that the railway track has a unique signature.
  - Complete characterization of the track.
  - Test and calibrate of the speedometer prototype.
  - Test and calibrate of the positioning system.
  - Detect damages on the sleepers.
  - Detect damages on the elements of the railway track (rail, clips, bolts etc.).
  - Detect abnormal elements on the track.
  - Take an inventory of railway track elements.
  - Use the positioning system in conjunction with the inspection system.
- Acquired data:
  - Profile of the track recorded by the two sensors reading the same points.
  - Vehicle speed with OBD-II to calibrate speedometer prototype.
  - Profile of the elements of the railway track inspected by the laser device.
  - Accurate positioning at every point of the test.
- Expected results:
  - Storage of the standardized stretch of track profile.
  - Comparison of the two repetitions of the entire stretch.
  - Individual characterization of each sleeper.
  - Speed accuracy of the prototype with respect to OBD-II.
  - Detection of possible damages in the railway track along with their position.
  - Determination of the severity of each damage using the readings taken by the laser device.
  - Inventory of the most important elements of the railway track and their condition.

3.6.3 | Test results

Although the tests were performed simultaneously, the results of the tests will be presented differentiating the two different systems that have been tested.

- Characterization of the positioning system

As in the test on the railway track 1 test, the first conclusion at a glance is that, qualitatively, the profiles of both the two radar sensors for each reading are very similar (Figure 23). Therefore, it can be uniquely determined that the railway track has a signature that is unique and corroborates the hypothesis on which the authors have developed this new positioning system.

As for the differences that can be seen within each graph, the analysis of the track has been split into two types of zones: (1) areas where the sleepers are exposed and (2) areas where the ballast completely covers the sleepers and where it would be necessary cleaning the railway track. Graphically, Figure 23

TABLE 6 Statistical results on the sleepers of railway track 2.

No. of sleepers	Average height	Standard deviation in height	Average width	Standard deviation in width	Track condition (0–3)
16,584	58.84 cm	2.15 cm	14.57 cm	1.22 cm	2.5

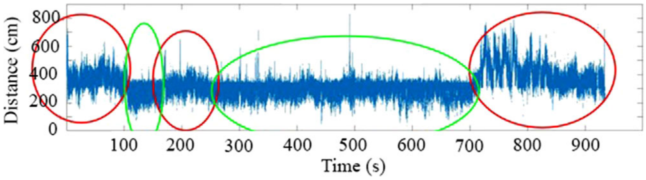


FIGURE 23 Track profile recorded by one of the two radar sensors, distinguishing 'clean' areas (circled in green) and 'dirty' areas (circled in red).

distinguishes these two zones, where 'clean' areas are circled in green and 'dirty' areas are circled in red.

Figure 24 is a close-up of a clean sleeper area, while Figure 25 shows a dirty area where ballast is placed over the sleepers.

Clearly, these graphs have pointed out the sleepers that are detected in each of the areas. As expected, the dirty areas that are covered by ballast hide much of the sleepers; those detected areas have a shape that determines the existence of a sleeper underneath, which is very useful for maintenance purposes. Therefore, the radar sensor is able to determine the dirtiness of the railway track 2 and also the condition, characterization and inventory of each one of the railway track's sleeper.

Again, like the results of the previous paragraph, a table is attached in Appendix 2 with the characterization of each of the sleepers that have been scanned along the route, with the same format and fields as for railway track 1 of Appendix 1. Taking into account these data, Table 6 shows the most relevant statistical results.

- Railway track inspection with the laser device.

The readings with the laser profilometer have two main objectives: The first one is to perform the rail inspection and the second is to perform the inspection of the railway fastenings of the rail to the sleepers (clips, bolts, washers, nuts, plates etc.). According to these objectives, the results that have been obtained in the tests carried out are as follows:

A. Inspection of the rail:

The structure of a rail is usually divided into three different zones: foot, web and head. When performing an inspection of the railway rail, it is important to determine not only the possible cracks and wear of its elements but also its position. The left of Figure 26 shows a 2D reading of the railway track 2, while the right represents a 3D scanning of a short segment of the same railway.

The technology proposed in this work is able to determine areas that can compromise safety, such as wear and tear. This is achieved by comparing the shape of the rail profile along the railway track, as registered by the laser profile, with the theoretical cross section of the rail, and then measuring the drift that exists between both shapes.

In the rail inspection measurements of railway track 2, we have detected a fissure that we determine as severe and several imperfections due to the accumulation of ballast in the web of the rail. Table 7 lists the most relevant imperfections detected during the railway track inspection and the confirmation after a visual inspection.

A. Inspection of railway fastenings:

The purpose of this type of inspection is to perform a scan of the status of the railway fasteners, including clips and bolts, as well as their preserved condition.

Figure 27 (left) shows the laser beam that scans the profile and registers the shape of a clip along with the bolt, while the right-hand side of the same figure displays the three-dimensional reconstruction of the same fastening as recorded by the laser device. As can be seen, the latter is able to accurately determine the damage or loss of a clip, as well as the situation of the bolt with respect to it.

In this way, Table 8 summarizes the results of the measures of all fasteners that have been analyzed in railway track 2.

3.7 | Test 4 on railway track 1

Once the previous set of tests on railway track 2 were performed satisfactorily, new tests on railway track 1 were carried out in order to acquire the readings of the profilometer (laser device). This is possible after having improved the stability of the measurements thanks to the use of the new anchoring method (Figure 21), as well as the creation of a shadow zone that allows the laser profilometer to be used in more tolerant light conditions (Figure 22).

3.7.1 | Tests design

The tests that have been carried out are only to perform the inspection of the railway track with the laser device:

- Visual inspection of the track and its shortcomings
  - Tests carried out:
    - Two repetitions in a single direction on the track with the laser profilometer.
  - Objectives

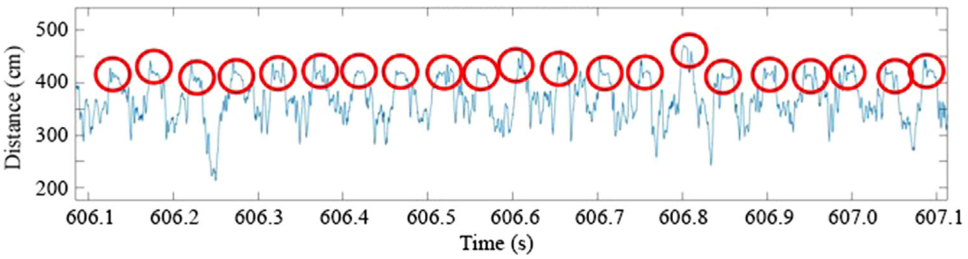


FIGURE 24 Close-up of a 'clean' sleeper area.

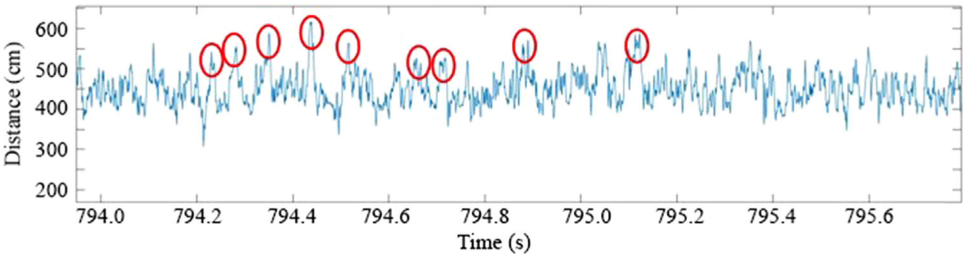


FIGURE 25 Close-up of a 'dirty' sleeper area.

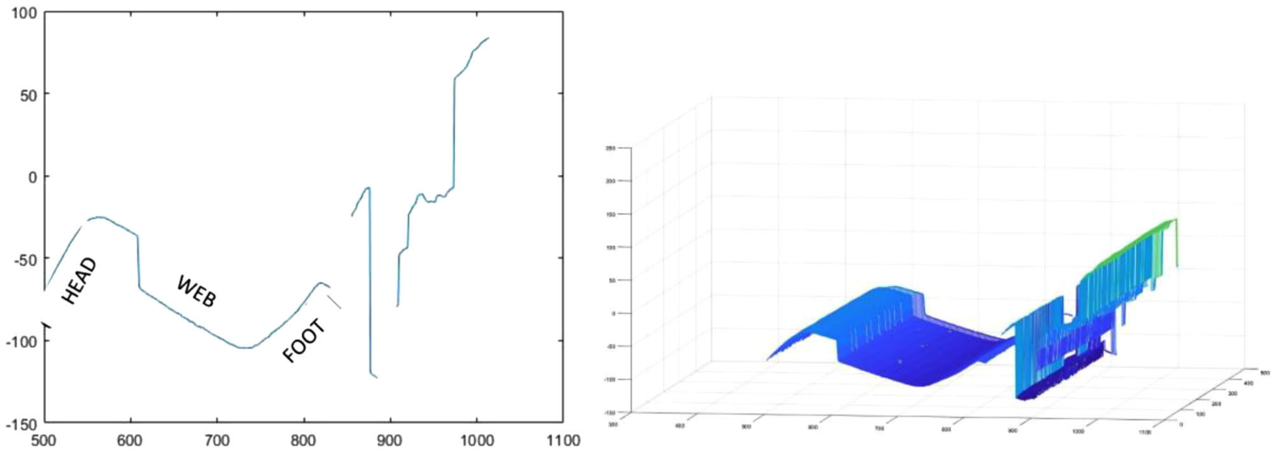


FIGURE 26 Examples of readings of the railway track 2 with the laser device, in 2D (left) and 3D (right).

TABLE 7 Imperfections after inspection of railway track 2.

No.	Approx. location (m)	Severity	Possible failure	Visual inspection	Severity after inspection
1	1200	Low	Fissure	Mild rail deformation	Low
2	4500	Medium	Ballast	Ballast accumulation	Medium
3	4700	Medium	Ballast	Ballast accumulation	Medium
4	4800	Medium	Ballast	Ballast accumulation	Medium
5	6400	Low	Fissure	Deformation	Low
6	7200	Low	Ballast	Ballast accumulation	Low
7	8100	Medium	Ballast	Ballast accumulation	Low
8	9300	High	Fissure	Opening in railway switch	None

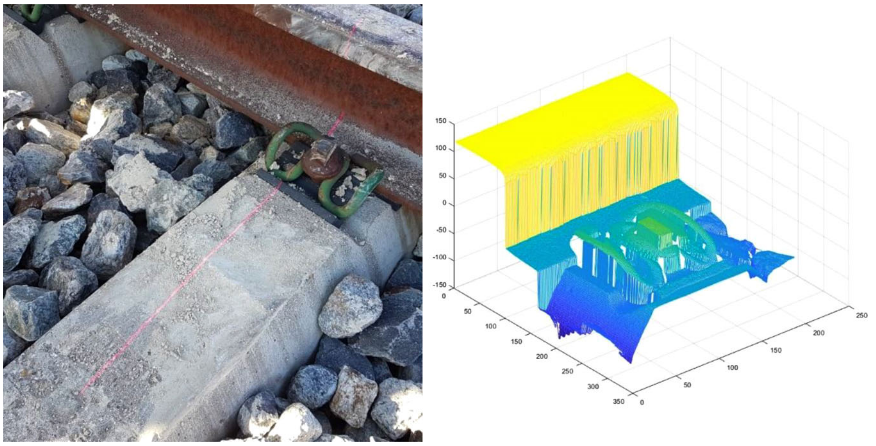


FIGURE 27 Laser beam scanning the fastening system (left) and its three-dimensional representation (right).

TABLE 8 Statistical results on the sleepers of railway track 2.

	Number	Good condition	Medium wear and tear	Severe wear and tear	Absence
Clips	32,843	90.2%	4.8%	0.2%	4.8%
Bolts	32,843	90.2%	4.7%	0.2%	4.9%

TABLE 9 Inventory of fasteners depending on their preserved condition.

	Number	Good condition	Medium wear and tear	Severe wear and tear	Absence
Bolts	4254	40.4%	27.2%	32.4%	18.7%
Junction flanges	72	31%	43%	26%	0%

- Detect damages on the elements of the railway track (rail, clips, bolts etc.).
- Take an inventory of railway track elements.
- Use the positioning system in conjunction with the inspection system.
- Acquired data:
- Profile of the track recorded by the radar sensor to position the vehicle.
- Vehicle speed with OBD-II to normalize profiles.
- Profile of the elements of the railway track inspected by the laser device.
- Accurate positioning at every point of the test.

• Expected results:
  - Detection of possible damages in the railway track along with their position.
  - Determination of the severity of each damage using the readings taken by the laser device.
  - Inventory of the most important elements of the railway track and their condition.

3.7.2 | Test results

The first part of the test consisted of a visual inspection of the damages existing on the railway track 1 and several problems were observed. After visual inspection, the railway track was inspected with the laser device, obtaining their three-dimensional representations of the detected imperfections. Real and represented images are presented in the following images, as follows:

- Poor condition of junctions with flange joint (Figure 28).
- Surface defects on railway rails (Figure 29).
- Lack of bolts (Figure 30).
- Bolts out of place (Figure 31).
- Damages on fixation plaques (Figure 32).
- Very bad condition of sleepers (Figure 33).
- Fixations covered by ballast (Figure 34).

Figure 34 shows, for instance, a three-dimensional representation of a clip with ballast inserted between its wings, which can generate a situation of danger and breakage in case of crushing or hitting. Therefore, this would be one of the situations that should be avoided and that need special maintenance of the railway track.

The next two tables try to summarize the preserved condition of this particular railway track: Table 9 recaps the inventory of fasteners classifying them upon their preserved condition, and Table 10 lists the 20 most severe potential pathologies that have been detected on the railway track route 1.

4 | CONCLUSIONS

In this study, we have monitored two railway tracks in very different states of maintenance, using different tools and devices, with the objective of testing a new system developed entirely by ADS. The main conclusions that have been obtained after performing the four sets of tests are the following:

4.1 | As for the positioning system

- It has been verified that the railway track has a unique signature (a surface identity) that allows the inspector vehicle to be positioned unequivocally.

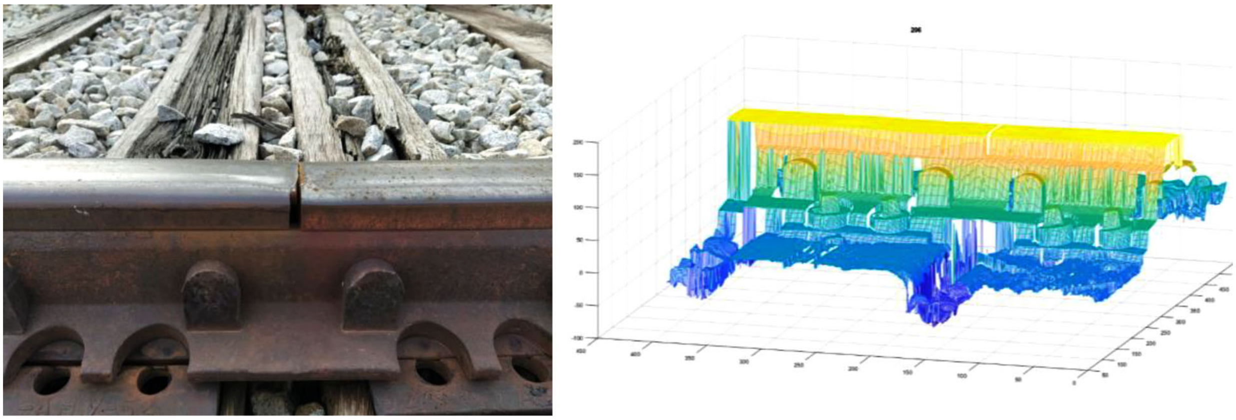


FIGURE 28 Poor condition of junctions with flange joint.

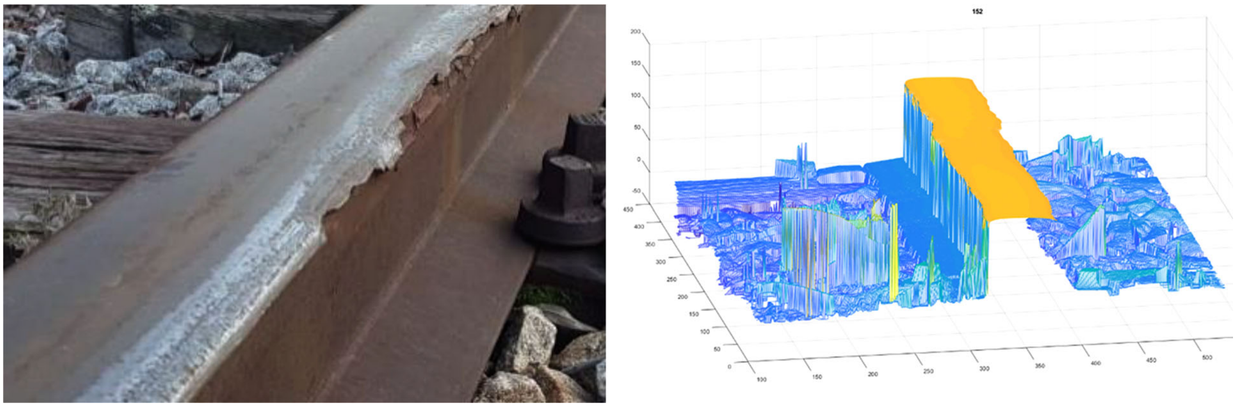


FIGURE 29 Surface defects on railway rails.

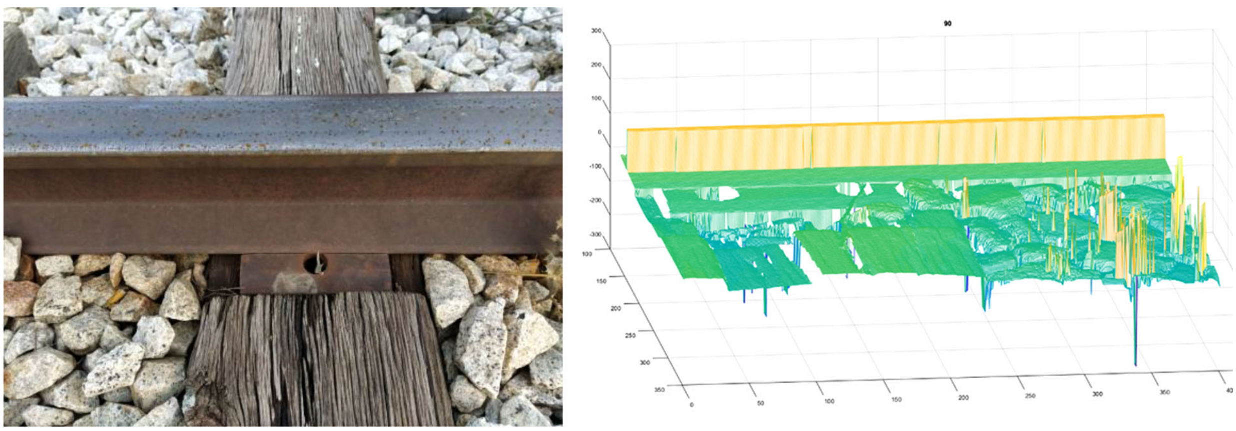


FIGURE 30 Lack of bolts.

- The radar system (which had never been used previously for this purpose) is capable of precisely positioning the vehicle on the railway track.
- The radar system is also capable of determining the exact speed of the vehicle at all times.
- The accuracy of the developed speedometer improves the accuracy of odometer-based speed measurement systems (OBD-II) by 5.8%.

4.2 | As for the inspection system

- The use of the radar sensor to inspect the railway track has been discarded because its current design is developed to focus its power on only 1 square centimetre, and therefore it is not wide enough to read the whole rail or fasteners.
- The inspection system based on a laser profilometer is very dependent on environmental light conditions; therefore, it

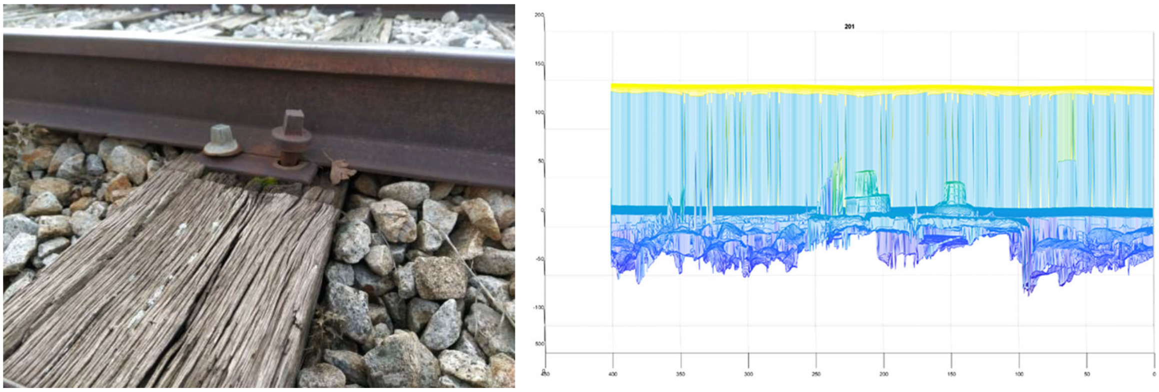


FIGURE 31 Bolts out of place.

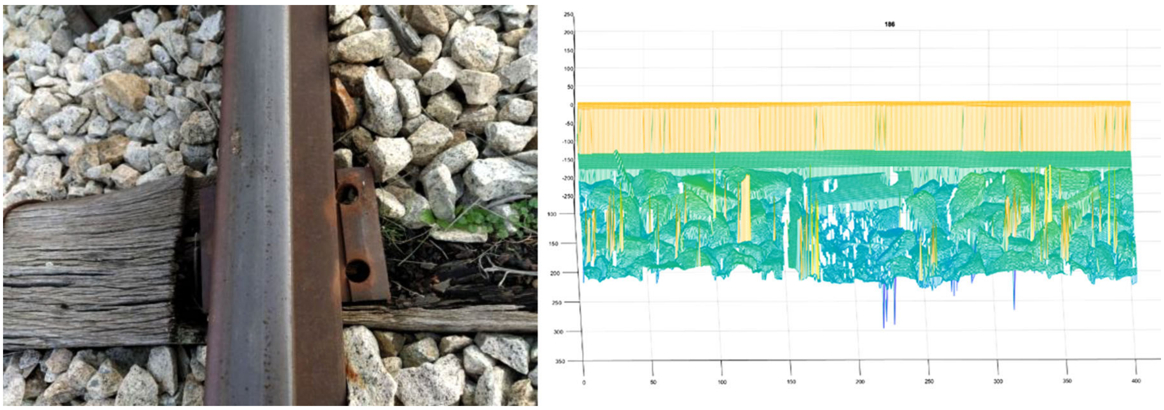


FIGURE 32 Damages on fixation plaques.

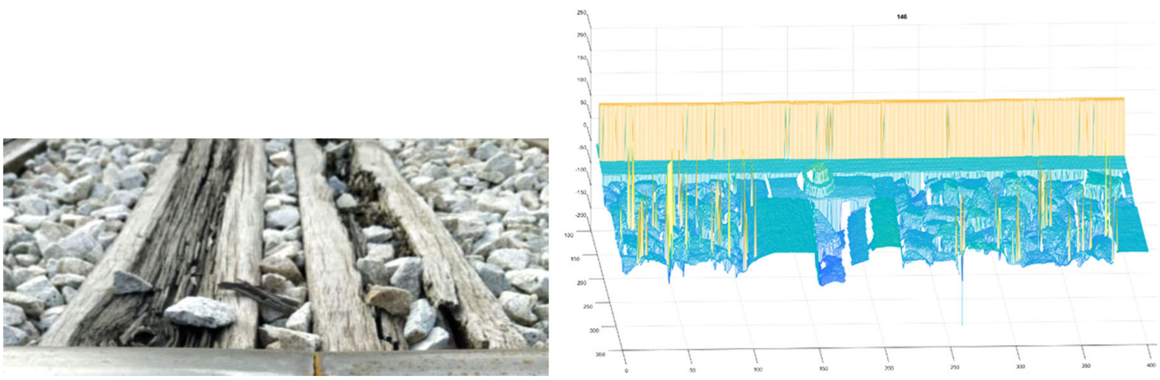


FIGURE 33 Very bad condition of sleepers.

is necessary to generate a shadow zone that prevents the detection of false positives in the fasteners.

- As for potential pathologies of the railway superstructure, the inspection system is able to detect the following problems: rail breaks, deformations or cracks on the surface of the rail, problems with fasteners (misplaced or absent) and determination of the condition of sleepers.

While the designed radar system is capable of working at speeds of up to 350 km/h, the laser profilometer is limited to 80 km/h under favourable light conditions, due to its data collection speed.

4.3 | Future developments

We have identified some possible improvements of the inspection system of the railway track

- Introduction of an optical capture system capable of taking images of the railway track in positions determined by the

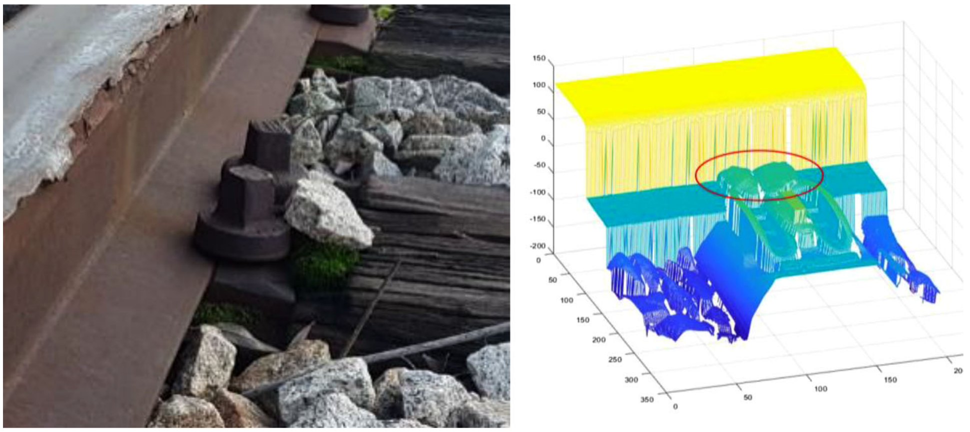


FIGURE 34 Fixations covered by ballast.

TABLE 10 Most severe pathologies detected on railway track 1.

No	Location (m)	Severity	Possible failure	Real failure [a]	Severity [a]
1	154	Very high	Rail breakage	Joint without welding	Medium
2	285				
3	21				
4	758	Very high	Poor condition of flange joint	Junctions with flange joint	Very high
5	63				
6	176	Very high	Missing bolt	Missing bolt	High
7	853				
8	241				
9	386				
10	147	High	Rail surface defect	Rail surface defect	Medium
11	586				
12	493	High	Bolt out of place	Bolt out of place	High
13	120				
14	51				
15	574				
16	698				
17	180	High	Poor condition of fixation	Fixation covered by ballast	Low
18	234				
19	482				
20	778				

[a] After visual inspection.

inspection system as damaged areas or with potential problems. Those images can be post-processed automatically or can be used as a visual support system.

- Improvement of the assembling of the equipment to fix the measurement systems to the draisine, which will make it steadier and will reduce possible errors due to vibration.
- Design of an array of radar sensors, or adding new optics allows their inspection zone to be expanded, so that they can be used as an inspection system.
- Detection of other problems such as cracks in the foot or web of the rail, requiring a new lens design for the radar sensor capable of focusing on these points, in addition to the railhead.

AUTHOR CONTRIBUTIONS

Valentin Gomez-Jauregui: Conceptualization; Investigation; Supervision; Writing—original draft; Writing—review & editing. Alejandro Badolato: Conceptualization; Formal analy-

sis. Juan de Dios Sanz Bobi: Conceptualization; Resources; Writing—review & editing. Ana Carrera-Monterde: Data curation; Investigation; Supervision; Writing—review & editing. Cristina Manchado: Investigation; Validation. César Otero: Project administration, Supervision, Writing – review & editing

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CONFLICT OF INTEREST STATEMENT

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DATA AVAILABILITY STATEMENT

Data available in article supplementary material. The data that supports the findings of this study are available in the supplementary material of this article in the form of 5 Appendices.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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