RailCheck: A WSN-Based System for Condition Monitoring of Railway Infrastructure

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Abstract—**Contemporary tools used to monitor railway points and crossings are ineffective. Routine inspections of these critical parts are still being performed manually by specially-trained inspectors. This creates higher expenditure and makes infrastructure difficult to maintain. With the expected further expansion of the railway network, this exerts increased pressure on infrastructure managers to ensure safe and predictable traffic. Hence there is a need for inexpensive and reliable condition-based maintenance systems. This paper describes an autonomous, near-real-time system built to this effect. It is based on acceleration measurements of train-track interaction, when the train is present. Using a wireless sensor network (WSN), data are aggregated over the Internet of Things (IoT) low-power wide-area network (LPWAN) structure into the Internet, where the big-data post-processing is performed. The performance and suitability of this system were evaluated on tracks in real traffic conditions and were found to be potentially beneficial for this sector. The system was built over a three-year period as part of the DESTinationRAIL H2020 EU-project.**

Keywords—**IoT, condition monitoring, condition-based maintenance, LPWAN, WSN, LTE-R, IQRF, railway**

I. INTRODUCTION

Worldwide railway networks have more than 1.15 million km of rail tracks [1], with further expansion planned. This inevitably requires methods and tools for the effective health monitoring of these large transportation networks.

Rail tracks without points and crossings are today regularly inspected by equipped maintenance trains that use camera or laser-based systems to automatically evaluate their condition. These tools, especially the laser-based solutions, can operate at very high speeds of up to 450 kmh^{-1}, and are an effective solution to gathering a large number of very precise datasets that can be further processed with relative ease. A support decision system can autonomously conclude where to increase inspection intervals, set a schedule for maintenance, and decide which rails needs to be fully replaced, having reached the end of their life. Before these methods existed, railway inspectors were dependent on many local measurements which were performed manually and one at a time. Decisions to replace tracks were frequently made at inappropriate moments, sometimes long before it was necessary or much too late in the life-cycle of the track. Contemporary tools for monitoring the geometric quality of tracks allows more frequent inspection, predictive maintenance control, and use of the existing infrastructure with high efficiency throughout the whole life-cycle.

The situation at railway points and crossings (P&C), on the other hand, is significantly different. Existing tools for monitoring degradation processes on P&C are not fully applicable on these parts. Furthermore, track-stiffness-monitoring vehicles cannot be used for these sections either. While spending on the maintenance and renewal of rail track without P&C is constantly optimized, expenditure on P&C has remained rather rudimentary over the decades. Degradation processes are still solely inspected manually, which, in combination with the large number of these parts, leads to high spending and ineffective maintenance. In some countries [2] about 25% of all maintenance costs are still being allocated to these critical parts. To resolve this disproportion new systems must be developed. One such system, RailCheck, has recently been introduced by Norwegian University of Science and Technology as part of the DESTinationRAIL [3] project.

II. STATE OF THE ART

Systems addressing this problematic are usually train or infrastructure-based or a hybrid of both.

Train-based solutions use sensors mounted on the train's suspension to evaluate responses from the tracks. The advantage of this method is its ability to filter out, to a certain extent, the response of its own, suspension. The disadvantages are the large amount of captured data and difficult recognition of the current position over the specific P&C. The train-based solution may be the most interesting future method, since modern trains are often already equipped from stock by very precise vibration sensors for the train's own self-diagnosis. If these data become accessible they might offer a very cost-effective and elegant way of gathering large numbers of representative datasets.

Infrastructure-based solutions [4] are currently the most feasible approach to railway condition-based maintenance. Stationary sensors mounted directly on the rails detect vibrations from passing trains at specific preselected P&C, and data are transmitted through existing GSM/WLAN infrastructure. The main disadvantage is the higher cost due to the large numbers of sensors in the network.

The hybrid solution [5] is usually an attempt to use stationary sensors mounted on the rails and a gateway located on the train. The main difficulty is the transmission of data between the fast-moving train and the sensors.
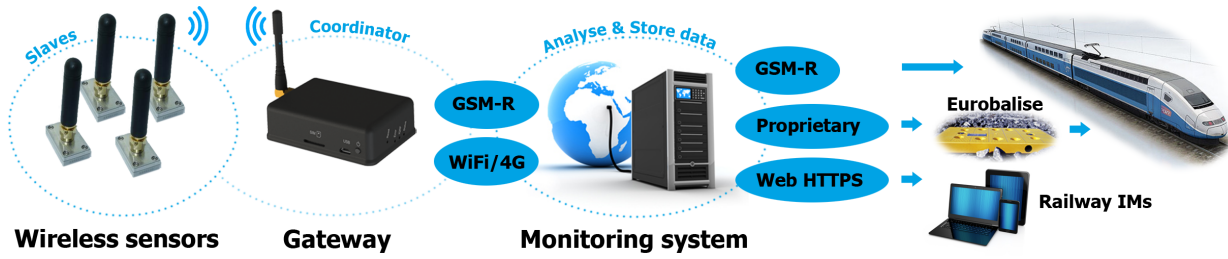
Fig. 1. Proposed condition monitoring system

III. Proposed Concept

As the RailCheck system was built as a deliverable of the DESTinationRAIL EU project [3], many of its operational parameters were already defined. Thus this concept could become the base solution for other, similarly defined systems.

Due to the large number of P&C in the railway infrastructure there is a large demand for systems that are both reliable and inexpensive. These two parameters can be broken down into detailed sub-terms, each with its own implications. The system must be secure, safe, maintenance-free and easy to deploy. It is assumed that solutions will be wireless and battery-powered, and will allow a high level of integration with existing and future railway structures. There are also performance-related requirements: the system should operate continuously in real time, and be capable of processing and storing data to enable the next steps in autonomous monitoring.

The proposed sensory system shown in Fig. 1 is based on common IoT LPWAN conventions. It provides autonomous near-real-time data acquisition, data aggregation and processing, and forwards information on the state of the infrastructure to stakeholders. Passing trains, both ordinary and monitoring, have access to these data. WSN and its support decision part facilitates responses to unexpected critical situations and the performance of optimal condition-based maintenance.

The basic idea for the data processing is based on long-term monitoring of the same unique trains over time based on prior knowledge of their configuration and cruising speed. E.g., by monitoring just one specific train every day, gradual changes in train-track interaction can be observed. The collected data would contain information about the train's suspension, the state of the track, and unpredictable events such as the impacts of a train's wheel flange hitting the rail head. This will make it possible to distinguish between the sources of such events and suggest actions to optimize spending.

A. Wireless Sensors

Wireless sensors in LPWAN are often battery-powered and are designed to operate for up to more than a decade. To achieve this, the sensors must sleep most of the time and only wake to perform their monitoring and communication tasks. The average current in sleep mode is typically at nA scale and μA during monitoring, sometimes rising to units of mA for radio frequency (RF) transmissions. Efficient power management and low costs are the most important requirements for the hardware.

1) MEMS Accelerometer: Most of the current measurements on the rails are performed by industrial-grade sensors that capture data at high sampling frequencies of 10-25 kHz, and measure acceleration up to ± 500 g. For our application this is less than ideal, due to the high initial costs, high power consumption, large size, lack of connectivity and difficult power-efficient transmission of generated data. In addition, these instruments are usually general-purpose, which can result in unneeded data and subsequently in unnecessary processing and communication. The primary objective therefore was inexpensive sensors with a limited range and data sampling-rate that could provide usable data, containing all the necessary information. Based on Fabien's [5] findings, a four-dollar MEMS accelerometer, ADXL313 [6], commonly used in consumer electronics, was selected. It has a limited dynamic range of ± 4 g with a maximum sampling rate of 3.2 kHz and uses barely 170 μA of energy. The sensor consumes 55 μA during sleep and has a wake-up feature. The indisputable advantages of using this consumer-grade sensor are the desirable price and the low power consumption.

2) Battery & Power Supply: Applications designed to last for decades require new approaches to power management. Commonly used batteries self-discharge too fast, therefore a 7.7 Ah cells based on Lithium-Thionyl chloride (Li-SOCl2) chemistry were necessary. These are designed specifically for long-term, 3-15 year application, and featuring a few μA base current. They are intended for periodic pulses, typically in the 5-150 mA range. Similar considerations apply to the voltage regulator, which has to have very high efficiency and a low quiescent current. Therefore LTC3335 [7], a nano-power buck-boost DC/DC with an integrated coulomb counter, was chosen. This regulator can monitor how much energy has already flowed through its circuits.

3) Wireless Communication: The sensors' wireless transmission is among the most energy-demanding tasks, and is therefore typically reduced to the minimum necessary. The market offers various solutions with transceivers with differing transmission speeds and ranges, frequencies used, protocol overheads, costs, and predominantly power consumption. The ISM band SRD860 with peer-to-peer communication was chosen based on the Spirit1 circuit [8]. This uses GFSK modulation and AES-128 encryption, and with an actual transmission rate of 19.8 kbps it can deliver data up to a distance of 500 m with 21.5 mA current consumption. This

device can stay responsive in receiver mode with just 16.3 μA of energy overheads. To reduce the power consumption and overall costs, the wireless module's microcontroller was also used for all of the sensor's processing and control tasks.

4) Sensor Casing & Location: The wireless sensor's integral casing contains all the crucial parts needed to power the circuits, record acceleration data from the approaching trains, and to store and eventually pre-process these data before transmitting them to the LPWAN. The compact casing simplifies handling, allowing rapid and easy deployment.

The position of the sensors on the rails was selected based on current legislation (Norwegian, also applies in the EU), RF propagation properties tested at Chapter IV-C, and previous research examining how acceleration varies with different measuring locations [9]. Six preselected positions on a rail head, rail web and rail foot between and above the sleeper, and two locations on top of the sleeper, in the middle and at one end, were evaluated. It was decided to use the upper part of the rail web directly below the rail head between the sleepers for the rail measurements (Fig. 2c), and the middle of the sleeper for sleeper measurements. The rail casing (Fig. 2b) is currently compatible with two types of rail profile: 54E3 and UIC60. Universal casing (Fig. 2a) supports horizontal or vertical mounting, e.g. on the railway sleeper.

The sensor casing was designed to address the requirements of chemical stability, durability, casing stiffness, waterproofness and signal propagation. Emphasis was placed on limiting the vibrations and resonant frequencies that would otherwise lessen the value of the measurements from the rails. ABS plastic, used in early prototypes, was found to be unusable due to its sensitivity to UV light and lack of chemical stability. Polyamide PA2200 was used as a replacement.

B. Gateway

The gateway is the main element in the communication chain, with unidirectional control over the sensors. A coordinator-node half-duplex communication is realized with a line of sight of up to 500 m. The gateway is placed close to the sensors, usually along the rails on the catenary mast (Fig. 2d), and creates a local cell with the sensors that it covers. The gateway accepts commands from parenting structures; however, it decides the order of their execution based on its current state. This creates a robust, distributed and highly scalable system. The gateway is responsible for the wireless sensor actions, for data consistency, and for forwarding the data and other (meta) information to the Internet-based storage.

1) Electronics: The original idea, to use third-party products, a combination of IQRF Gateway [10] and IQRF Cloud [11], was found to be incompatible with the qualitative requirements of the DESTinationRAIL project [3], primarily due to the undocumented bottleneck between these two parts. Therefore a dedicated gateway of our own design was built to address the project's requirements. The effective radiated power (ERP) was increased by a front-end module (FEM) [12] and a SRD868 10 dBi Yagi antenna from 12.5 mW to 500 mW. The receiver's sensitivity was increased by the same measures.

(a) Universal

(b) Rail web

(c) Rail attachment

(d) Gateway coverage on a railway points
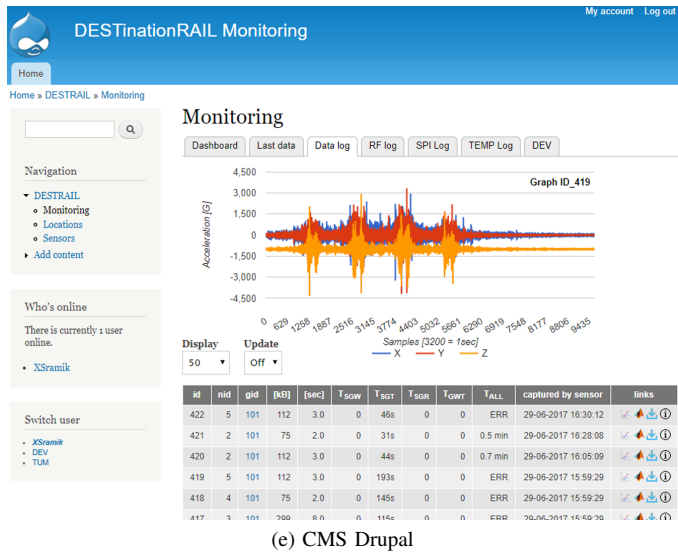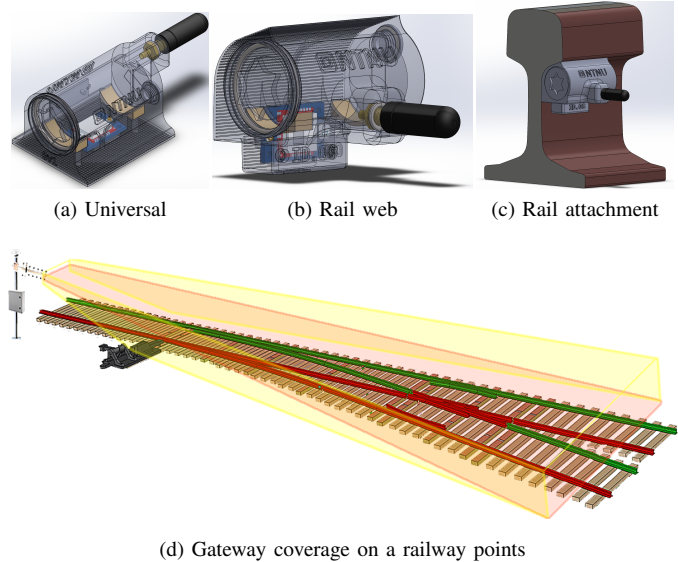
(e) CMS Drupal

Fig. 2. Wireless Sensor Casing (a,b,c); Gateway (d); Web server (e)

Support for communication over both WiFi 802.11ac and LTE networks (LTE-R in future revisions) was added to the design.

2) Gateway Casing & Location: The gateway electronics were enclosed in a cabinet of 300x200x150 mm, with provisions for mounting it on a pole or catenary mast. The Yagi antenna was directed along the rails towards the sensors.

C. Web server

The web-based content management system, Drupal [13] (Fig. 2e), serves several purposes. Mainly it is used as an aggregation point for all of the sensor's data, which are stored, analysed and displayed in context here. Authorized users are granted access through the HTTPS protocol and can use various services, such as export to MATLAB, for subsequent work. Data can also be automatically propagated to key stakeholders such as railway inspectors, passing or monitoring trains.

IV. EVALUATION

This section describes the evaluation primarily of the hardware. A detailed evaluation of the data from the experiments is being prepared for publication in a railway-specific journal.

A. Feasibility test

A feasibility test of the preliminary concept was performed during the first stage of the project to assess the performance of the crucial components and their key features and parameters. The main concerns were the accelerometer's capability to wake up the electronics on an approaching train[1], its response on an overpassing trains[1] and the ability to transmit the data acquired over radio frequencies, as elaborated in Chapter IV-C.

A measurement chain was assembled from several evaluation boards, as shown in Fig. 3a. The wireless sensor consisted of accelerometer EVAL-ADXL313-Z-ND [6], a battery-powered board DK-EVAL-04A [14], and an RF module TR-72DAT [15]. The gateway consisted of a second RF module, a programmer CK-USB-04A [16], and a computer. Measuring was triggered automatically by the oncoming train once the acceleration superseded the threshold specified. The data were automatically transmitted over the whole structure into the C# application running on the computer. The application recorded RAW data in the file and displayed them as a chart.

For practical reasons in this specific test, the accelerometer sampling frequency was set to 400 Hz with a gravity range of ± 2 g, and vertical axis measuring deflection only was recorded. According to similar measurements taken by Fabien [5], the selected magnitude of acceleration should be appropriate. The accelerometer was then attached to the rail web using four magnets with a total aggregated force of 28 kg, as shown in Fig. 3b.

Two passenger trains passing in each directions were recorded at a spot about 100 m from the railway station. The incoming train slowed down approaching the station and passed over the sensor as shown in Fig. 3c. Afterwards the train accelerated away from the station and in about 5 seconds passed over the sensor in the opposite direction. This time the measurement was triggered manually once the train moved from the station, as shown in Fig. 3d. The speed of the train over the sensor was in both cases approximately 10 kmh^{-1}.

Both of the measurements shown in Fig. 3c and Fig. 3d went into a saturation when the train's acceleration exceeded the selected magnitude. From this and further results obtained later, the following assumptions were made: firstly, as expected, a sampling frequency of 400 Hz is not suitable for such a measurement, since many of the useful data are filtered out. The 3200 Hz used in following tests appeared to be an adequate minimum. Secondly, accelerations measured by consumer-grade sensors, which have a lower sampling rate than commonly-used industrial sensors, are much lower than what these sensors usually measure. Thirdly, wake-up on the approaching train is possible due to the sensor's response time of up to 1.4 ms at 3200 Hz, when the acceleration rises over the selected threshold[1]. The accelerations of about ± 100 mg
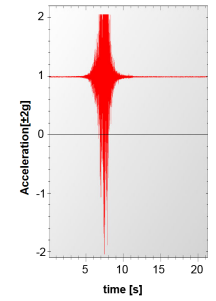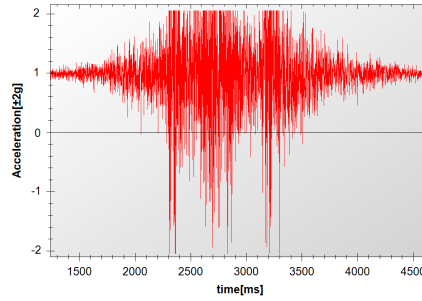

(a) Testing structure

(b) ADXL313 Evaluation board attached to the rail web

(c) Train pass 1

(d) Train pass 2

Fig. 3. Feasibility test

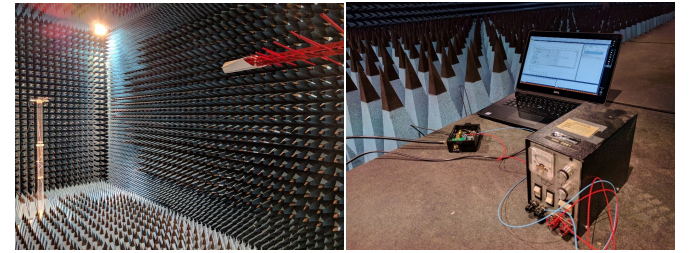

(a)   (b)

Fig. 4. Anechoic chamber test

1 sec and ± 200 mg 400 ms were sensed before the train passed over the sensor at 160 kmh^{-1} during another test.

B. Validation of Gateway ERP

Before the system could be used outside the controlled environment it had to be verified against current legislation, which is governed by ETSI regulation for SRD860 devices operating in the ISM band: ECC Recommendation 70-03 [17]. This was done in an anechoic chamber, as shown in Fig. 4, where all the parts involved in signal propagation were validated as a whole against the reference antenna. Due to known RF attenuation in used coaxial cables and air attenuation of known distance, the correct parameters were calculated and set to the RF circuits. This allowed us set the output constants properly and verify that not more than 500 mW ERP will be radiated from the

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[1]Data are being prepared for publication in a railway-specific journal.

gateway, to prevent RF interference between various systems, which could be dangerous, especially on the railway.

C. Verification of coverage between sensors and gateway

The practical evaluation was performed on a stacking track, as shown in Fig. 5a, in cooperation with Bane NOR. Sensors were deployed at 30, 60 and 90 m from the gateway, which was attached to a pole of height 1.3 and 2.2 m. The 30 m point was marked with an orange-and-white traffic cone, an orange-and-yellow traffic cone next to the concrete sleepers marked the 60 m point, and for the 90 m point, the gateway was relocated 30 m backwards along the track.

The results presented in this chapter are indicative only and are not statistically significant, nor are they necessarily representative of other sites or weather conditions. The tests were performed within a limited time span, with the main purpose to evaluate the reliability of the communication between the sensors and the gateway. For general applicability and statistical validity we would need long-term installations in several places, something that clearly must be done before the commercialization of this concept.

The main concerns regarding signal propagation due to the deployment of sensors directly to the rail body appeared to be valid. Signal propagation from the sensor was highly affected based on the antenna's location against the rail. Even small changes in location from the first prototype to the second were reflected by an increase of 6 dB at some of the measurements. This was achieved by moving the antenna from the rail web about 2 cm vertically and 2 cm horizontally from the rail body. Another positive finding was that the 10 cm column of snow shown covering the sensors in Fig. 5d, did not reduce signal quality. This was probably strongly affected by the favourable weather conditions with several cold days ahead of the test, the snow was therefore very dry. Trains passing during active transmission did not seem to interfere with communication.

Due to the limited length of the stacking track, the communication between sensors and gateway was tested only to a distance of 90 m. The gateway was located on a pole 2.2 m above the terrain and the sensors were covered by a 10 cm column of dry snow. The test was performed in favourable weather conditions: a sunny day with $-12°C$. Reliable communication was achieved with a signal strength of over -62 dBm. With receiver sensitivity of -115 dBm and the presumption that each 6 dB gain doubles the effective range, reliable coverage of 250 to 500 m can be expected.

V. Conclusion

Results from a designed, implemented and deployed WSN-based system, RailCheck, revealed that even inexpensive consumer-grade accelerometers may be suitable as a basis for obtaining necessary data for the purpose of condition monitoring and subsequent condition-based maintenance of railway tracks, points and crossings. Affordable wireless sensors costing about € 20 per unit might accelerate the use of these sensors and allow their deployment on a large scale. The results and experiences of this project indicate that systems
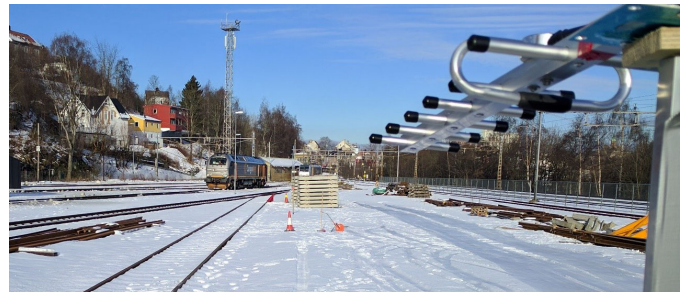
(a) Antenna coverage test

(b) Gateway location (c) Sensor placement (d) Sensors under snow

Fig. 5. Coverage test

such as the one presented here will have a crucial role in future transportation systems.

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