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Proceeding Paper

Development of a Zigbee-based wireless sensor network of MEMS accelerometers for pavement monitoring †

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Abstract: Safety related to pavement ageing is a major issue, as cracks and holes in the road surface can lead to severe accidents. Although pavement maintenance is extremely costly, detecting a deterioration before its surface gets completely damaged remains a challenge. Current approaches still use wired sensors, which consume a lot of energy and are expensive; further than that, wired sensors may get damaged during installation. To avoid the use of cables, in this work a prototype of Zigbee-based wireless sensor network for pavement monitoring was developed and tested in the laboratory. The system consists of a slave sensor and a roadside unit: the slave sensor sends wireless acceleration data to the master, and the master saves the received acceleration dataset in a csv file. Further data processing can be performed in the master on this acceleration dataset. Two laboratory test performed for dynamic calibration, and simulating five axle truck pavement displacement. Preliminary results showed that the Zigbee-based wireless sensor network is capable of capturing the required ranges of displacement, acceleration and frequency. The ADXL354 sensor was found to be the most approriate accelerometer for this application, with as small as 155 uA power consumption.

Keywords: pavement monitoring; wireless sensor networks; MEMS accelerometers; Zigbee

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1. Introduction

Detecting a deterioration in pavements before they get totally damaged, remains a costly and very challenging task. Many devices have already been proposed, but most of them still use wired sensors; more and more researchers are currently investigating pavement monitoring systems being low-cost, low-energy, and wireless. Geophones, accelerometers, and strain sensors are usually used to monitor pavement condition by measuring strain, displacement, and vertical velocity of the pavement. Many proposed setups still use cables. The monitoring system described in [1] was based on strain gauges, soil pressure gauges used as load cells, thermocouple temperature sensors, and moisture sensors embedded into the pavement. All these sensors are connected to a data logger on the roadside via cables. Geophones are used in the system presented in[2] to measure the vertical velocity at the pavement surface, and convert it into vertical displacement (deflection). Other systems are based on MEMS accelerometers [3]–[9], packaged in a nylon box or covered with resin. These accelerometers are buried into the pavement and then connected to the data logger or master, which is placed next to the road. In the case of exploitation of data collected with geophones or accelerometers, the measurements are converted into vertical displacements by signal processing using integration [6,8].

On the other hand, thinking of a digital twin of the system, finite element (FE) modeling can be used for the analysis of flexible pavements. In [10], a three-dimensional (3D)

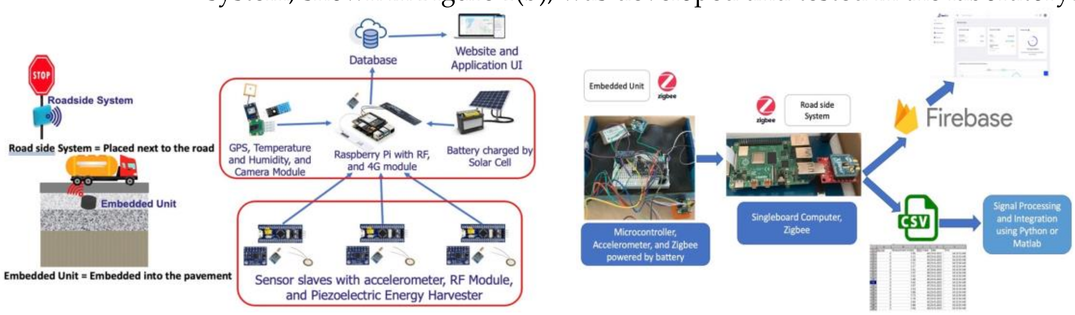
FE analysis was carried out on a portion of a flexible pavement to predict rut depth under different conditions of temperature, loading, and for different material properties. Another 3D pavement FE model was described in[11], to assess the influence of truck parameters such as wheel set, axle set, vehicle travel speed, and tire pressure on rutting. In this work, a preliminary study carried out using the state-of-the-art ABAQUS software, to model the pavement response and understand the specific effects of moving loads. This analysis enabled us to evaluate the magnitude of the displacement at the surface of the pavement, under moving vehicle loads. This was used to define displacement signals for the vibrating table tests but also to predict the response in full scale tests carried out on the fatigue Carousel available at Univ. Eiffel in Nantes. The fatigue Carousel is an accelerated pavement testing facility, which allows testing our sensor prototypes under real-life conditions.

In this paper, a novel pavement monitoring system was thus built around a Zigbee-based wireless sensor network prototype, and tested in the laboratory. This prototype aims to solve the current problem related to the costs of the monitoring system, getting rid of cables and heading towards the lowest possible power consumption. MEMS accelerometers were chosen because they are easy to integrate, less costly than other sensors and consume little energy. Three MEMS accelerometers were selected for comparative evaluation in the prototype, under two laboratory test conditions. The Zigbee communication protocol was chosen primarily because it has the lowest power consumption in both transmit and receive modes. According to the literature, the measured deflection of the pavements should be between about 0.1 mm and 1 mm with a frequency ranging from 0.5 Hz to 20 Hz, resulting in acceleration values from 5 mg to 200 mg. The sensor and system must therefore be able to operate in the low g and low frequency acceleration ranges.

2. Materials and methods

2.1. System architecture and prototype

The prototype developed was based on the architecture shown in Figure 1(a). The on-board unit consisting of an ESP32 Pico-D4 microcontroller, a Zigbee module and an ADS1115 ADC. The microcontroller collects the accelerometer data either from the ADS1115, or directly via the I2C communication protocol or SPI for digital accelerometers. It then sends the data directly to the wireless road system using the Zigbee protocol. The road system receives the data from the on-board unit, saves it in a csv file and then processes it using the digital signal processing algorithm to be implemented. The prototype system, shown in Figure 1(b), was developed and tested in the laboratory.

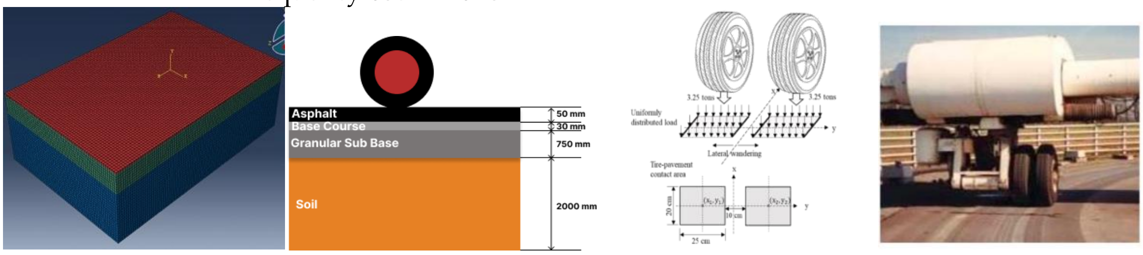


(a) (b)

Figure 1. (**a**) Proposed system architecture; (**b**) first prototype built.

2.2. Finite Element Modeling

A preliminary study using FE modeling was carried out to assess the response of the pavement tested on the fatigue carousel, subjected to moving loads. The pavement was modeled using the ABAQUS software. All the modeled pavement layers are shown in Figure 2(a); the same thicknesses and material properties were adopted as those of the pavement tested on the fatigue carousel. The pavement section consisted of four layers, from bottom to top respectively: a 2000 mm thick soil layer; a 750 mm thick granular sub-base layer; a 30 mm thick asphalt base course; and a 50 mm thick asphalt surface course. Infinite elements were used at the side and bottom surfaces of the model to dampen the propagation of waves, avoid spurious reflections and relevant artifacts in terms of high frequency oscillations.



(a) (b)

Figure 2. (**a**) 3D Structure and layer configuration of the pavement; (**b**) real loading condition.

The pavement of the fatigue carousel was loaded as depicted in Figure 2(b), by dual wheels with a total load of 65 kN. The load was assumed uniformly distributed over the tire contact areas. A dynamic moving load simulation was carried out to account for the effects of inertia and of the moving tire loads on the pavement. The dynamic simulation was performed using the VDLOAD user subroutine of the FE code, to allow the load to move across the structure with a speed of 6 m/s. The adopted values of material properties and layer thicknesses are gathered in Table 1.

Table 1. Values of material properties and layer thickness used in the simulation.

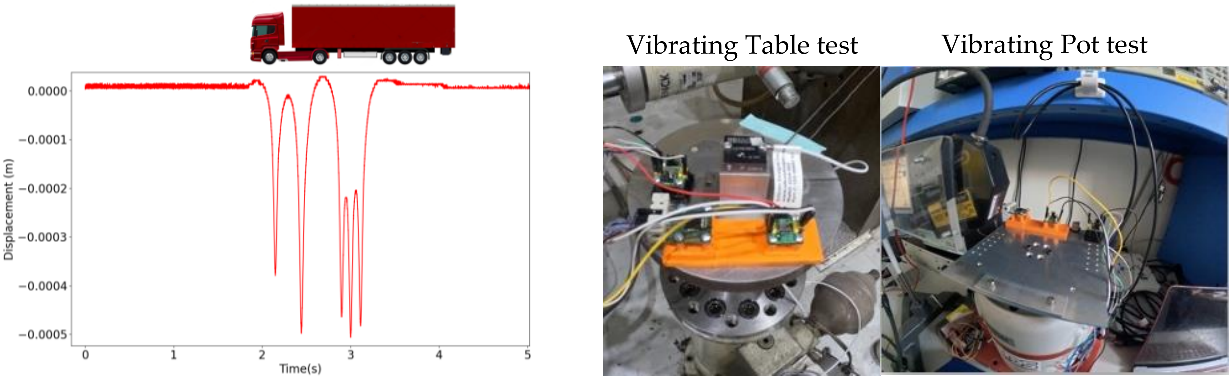
Layer	Young's Modulus E(MPa)	Poisson's ratio	Density (kg/m^3)	Thickness(mm)
Surface course	31,468	0.35	2400	50
Base Course	37,554	0.35	2400	30
Granular Sub Base	160	0.35	2400	750
Soil	95	0.35	2400	2000

2.3. Laboratory Tests

A first laboratory test was carried out using the vibrating pot available in the ESY-COM laboratory. This test enabled dynamic calibration of each sensor, and collection of important sensor characteristics such as sensitivity, noise, power consumption and resolution. The shaker used was the LDS V460, equipped with a Bruel & Kjaer PT01 feedback accelerometer to monitor vibration acceleration. A sinusoidal acceleration signal of low g and different frequencies was used to test three different accelerometers. The test setup is shown in Figure 3(b).

The second laboratory test was carried out using a vibrating table available at the SII laboratory of the Eiffel University in Nantes. The aim of this test was to observe the ability of the MEMS sensors and of the wireless sensor network to measure the signal typical of a five axle truck passing on the road. The vibrating table, manufactured by Team corporation, can be controlled on the move, as it is equipped with a Messotron LVDT WLC 100 displacement sensor. The signal from the displacement transducer was considered as the reference and used to compare with the displacements resulting from the processing of data collected by the accelerometers. The test configuration is shown in Figure 3(b). A typical signal from a five axle truck that was used for the laboratory test is shown in Figure 3(a). This signal was obtained from a previous experiment carried out by a researcher at

Univ. Eiffel in Nantes, which consisted in measuring the pavement response under loading of a reference truck on a freeway, using geophones and accelerometers, and then converting it into displacement.



(a) (b)

Figure 3. (**a**) Typical five axle truck signal used for the vibrating table test; (**b**) vibrating pot and vibrating table test configurations.

While on-board MEMS sensors measure accelerations, it is more relevant, for analysing the response of the pavement, to determine the displacement of the roadway. Acceleration can be converted into displacement using a two-stage integration. Digital signal processing is therefore required to convert the collected acceleration time history into displacement. This digital signal processing was performed in the master (Raspberry Pi) using python libraries such as numpy, scipy and matplotlib. The signal processing procedure for converting the raw acceleration signal into displacement was developed with concept based on [6] is sketched in Figure 4.

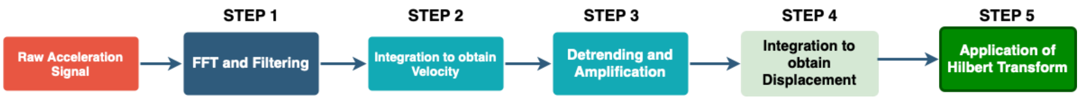
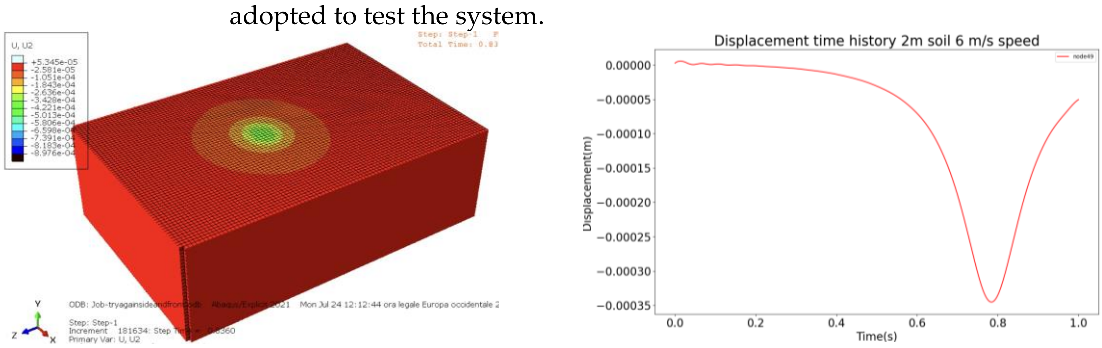


Figure 4. Signal processing method to convert acceleration into displacement.

3. Results and Discussion

3.1. FE results

Figure 4(a) shows the variation of the vertical displacement over the top surface of the pavement. The signals corresponds to the point where the countour provides the maximum deflection. The corresponding displacement time history at one node along the load path is represented in Figure 4(b). The results indicate that a displacement amplitude of approximately 0.35 mm can be expected for the pavement of the Fatigue Caroussel under such a load. Thus, during the laboratory tests, a displacement amplitude of this type was adopted to test the system.



(a) (b)

Figure 4. (**a**) contour plot of vertical displacement; (**b**) time history of the vertical displacement at one node.

3.2. Laboratory test results

Three MEMS accelerometers were tested: ADXL355, ADXL354, and MS1002. The test results are summarized in Table 2, which shows the output type, the sensitivity of each sensor, along with the power consumption and the noise.

Table 2. Sensor characteristics obtained with the vibrating pot test.

Accelerometer Type	ADXL355	ADXL354	MS1002
Output	Digital Output	Analog Output	Differential Analog Output
Sensitivity	-	384 mV/g	1340 mV/g
Power Consumption	 201.0 uA	 155.2 uA	 12.11 mA
Noise	0.0024 m/s^2	0.022 m/s^2	0.0076 m/s^2

It can be seen that the ADXL354 has the lowest power consumption compared with the other two sensors at 155.2 µA, while the MS1002 has the highest power consumption at 12.11 mA. The ADXL354 has an analog output with sensitivity of 384 mV/g. Thus, the ADXL354 seems to have the best characteristics for the pavement monitoring system, as it has the lowest power consumption and good accuracy.

The vibrating table test was carried out at a lower displacement amplitudes (0.25 mm) than the signal reported in Figure 4(b). This was on purpose adopted to observe whether the accelerometer sensor and the entire system were able to detect very low displacement/acceleration levels, since very low g's are expected to be measured.

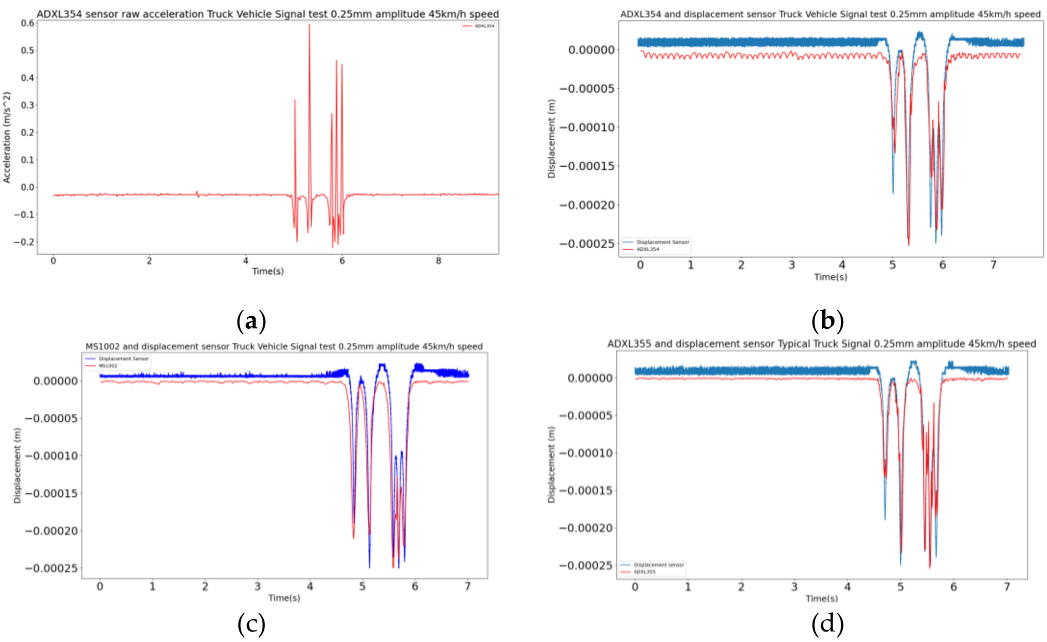


Figure 5. (**a**) Example of Raw acceleration signals from the test of the three sensors; (**b**)(c)(d) displacement conversion for all the sensors.

The example of raw acceleration signals are shown in Figure 5(a). The results of the test with a displacement amplitude of 0.25 mm at a speed of 45 km/h is shown in Figure 5(b)(c)(d). The result is compared with the signal from the vibration table's integrated displacement sensor, shown in blue. The results show that the proposed digital processing method was capable of converting the measured acceleration value into displacement. However, an error is still visible when comparing the signal-processed displacement with the displacement sensor data.

4. Conclusion

In this work, a prototype Zigbee-based wireless sensor network using a MEMS accelerometer for pavement monitoring was proposed, built and tested in the laboratory. A preliminary numerical study was carried out to assess the kind of deflection to be expected under the moving load induced by a full scale fatigue test. In this case, the prototype developed was used to comparatively assess the performance of three MEMS accelerometers by means of two laboratory tests, namely a dynamic calibration and the simulation of the displacement produced by a five-axle truck. A signal processing step was also carried out to convert accelerations into displacements. The results of the laboratory test showed that the system is capable of monitoring pavement deflections. Also, it has been demonstrated that the ADXL354 is the most suitable accelerometer, due to its low power consumption and good accuracy. The system will shortly be tested under real-life conditions at the accelerated pavement testing facility.

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