https://doi.org/10.31436/iiumej.v21i1.1223

# PAVEMENT CONDITION ANALYSIS VIA VEHICLE MOUNTED ACCELEROMETER DATA

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*(Received: 26th August 2019; Accepted: 27th November 2019; Published on-line: 20th January 2020)*

***ABSTRACT:*** Road anomalies and irregularities such as potholes and uneven surfaces are a common hazard in South East Asia and developing countries. Such hazards pose a threat to the safety and well-being of both civilians going about their daily routine and tourists who are exploring the city. Since bicycles and rickshaws are still a common mode of transport used by both civilians and tourists in many South East Asian countries, it is essential to improve the overall quality and smoothness of pavements which are traversed by these vehicles. Management of international sporting and recreational events also require satisfactory road and pavement conditions. Before pavement conditions can be improved, it is an essential prerequisite to obtain comprehensive information about road irregularities such as the location and also severity of the road irregularity (depth of the potholes and height of bumps). In this paper, we propose a method for obtaining mathematical models that represent the overall condition of the pavements that are part of a commonly traversed cycling route. Such mathematical models and coefficients can be stored in the cloud of an Internet of Things (IOT) data analytics systems subsequently leading to identification of regions with severe road irregularities.

***ABSTRAK:*** Kerosakan pada permukaan jalan raya merupakan salah satu faktor risiko kemalangan yang berlaku secara meluas di negara Asia Tenggara dan negara membangun yang lain. Memandangkan kenderaan seperti beca dan basikal masih diguna pakai secara meluas di negara membangun, adalah mustahak untuk membaik pulih kerosakan jalan raya. Pengurusan sukan antarabangsa dan rekreasi juga memerlukan keadaan jalan dan laluan pejalan kaki yang baik. Sebelum kerja membaik pulih dapat dilakukan, maklumat lengkap mengenai tahap kerosakan jalan raya dan lokasi kerosakan diperlukan. Dalam kajian ini satu kaedah telah diperkenalkan untuk mendapatkan persamaan matematik yang menggambarkan keadaan sebenar permukaan jalan raya, di mana sebahagiannya merupakan laluan berbasikal yang selalu digunakan. Model matematik dan pekali ini boleh di simpan dalam sistem analisis data awan Internet Benda (IOT) kemudiannya dapat mengenal pasti kawasan jalan yang rosak dan tidak rata.

***KEYWORDS:*** *road quality monitoring; accelerometer; vibrations; envelope detection*

## 1. INTRODUCTION

Cycling is increasingly becoming a preferred means of transport in developing countries due to the awareness of the benefits of daily physical activity and also the awareness of the importance of environmental preservation. In Kuala Lumpur, dedicated cycling lanes have been recently constructed to cater to the increasing number of Malaysian cyclists. Dedicated cycling lanes are a norm in developed countries such as Australia, the UK, and many parts of Europe. Ensuring the smoothness and quality of the roads and pavements is essential for the ride comfort and safety of cyclists and even pedestrians. Uneven surfaces and road irregularities may lead to trips and falls, thus endangering both cyclists and pedestrians alike. Before the local City Council utilizes materials, resources and manpower to repair uneven and irregular road surfaces, it is essential to obtain an overall representation of the condition of the pavements or roads in order to devise and optimal strategy for repair works that efficiently utilize existing resources and manpower.

In this paper, we develop mathematical models that represent the overall condition of a pavement by utilizing vertical Z-axis accelerometer data that have been collected by a sensor package mounted onto the handle of a bicycle. The Z-axis accelerometer data corresponds to vertical vibration of the bicycle, which directly corresponds to the condition of the road. A sensor package consisting of a combination of an ADXL 335 MEMS Accelerometer, an Arduino Nano Microcontroller, and an SD card (for data storage) are mounted onto a bicycle and the subsequent accelerometer data, reflecting the condition of the pavement, are collected and stored in the SD card for further offline data processing and analysis. Mathematical models that describe the condition of the pavement can then be obtained. The location of the pavement irregularity can be estimated with a mathematical model that represents the pavement condition and also takes into consideration the sampling rate used for the accelerometer measurements together with the distance traversed and time taken to reach the destination.

## 2. EXISTING WORK

Existing work regarding road quality analysis utilizing accelerometer data have focused primarily on the road quality analysis of larger roads such as highways. Therefore, in our study, in order to address the current research gap, we have chosen to analyse the road quality of pavements meant for cyclists and pedestrians that cannot be traversed by larger vehicles such as cars and trucks. Nevertheless we describe herewith recent work on road quality analysis to equip the reader with some background knowledge about the current state of the art.

Chenglong et al. developed a system to calculate the International Roughness Index (IRI) in real time based on road quality information collected from wireless accelerometer data and also vehicle position information collected from GPS data [1]. ZigBee and 3G based wireless communication was utilized to transfer information collected from the accelerometers and GPS to a central computer. Field tests conducted in selected locations in Zheijang demonstrated the feasibility of the proposed system to deliver real-time road quality information.

Xiao Li and Goldberg described the usage of citizen sensing or mobile crowd-sensing in which the public can utilize their smartphones, which have a variety of sensors, in order to collect data in the form of spatial series of the geo-referenced Z-axis accelerations of the road surface [2]. The collected data was then used to compute two novel assessment indexes that represent the road quality.

Harikrishnan and Gopi proposed a method to monitor road surfaces, detect potholes and humps, and predict severity by analysing the vertical vibration signals obtained as the vehicle moved along a particular road [3]. The inbuilt accelerometer inside the smartphone is used to capture the vehicle vibrations in which the z-axis reading corresponds to the vehicle vertical vibrations. A Gaussian model-based mining algorithm has been proposed for detecting road abnormalities. The X-Z ratio filtering had been applied for event classifying and discriminating potholes and humps. A severity estimation algorithm has been proposed that utilized the relation between vertical acceleration and relative vertical displacement of the vehicle. Wickramarathne, Garg and Bauer had developed a simplified approach towards characterizing road surface conditions from vertical acceleration measurements based on a signal transmission model that captures the complete system dynamics of the vehicle suspension system [4].

Mukherjee and Majhi had demonstrated the feasibility of using smartphones placed inside the vehicles in characterisation of road bumps. However, they highlighted that the smartphone's capability of discerning different types of speed bumps while travelling in heterogeneous vehicles is still an open problem [5].

## 3. MAIN WORK

The block diagram of the proposed methodology is shown in Fig. 1. Firstly, vibration signals that reflect the condition of the pavement are collected using a combination of an accelerometer, microcontroller, and SD card that have been mounted onto a bicycle. Alternatively, a portable Data Acquisition Device (DAQ), such as the NI-6008/6009 by National Instruments, together with a laptop could also have been used to record vibration signals from the output of the ADXL 335 accelerometer with a superior sampling rate. However, at this stage of the study, we desired to have a small, light, portable, and detachable package for measuring the vibration signals that reflect the condition of the pavement.

### 3.1 Data Acquisition

#### *3.1.1 Accelerometer Sensor Package*

For this system, we have developed an Accelerometer Sensor Package that consists of an ADXL 335 Microelectromechanical Systems (MEMS) accelerometer, an Arduino Nano Microcontroller, a Micro SD card that is used together with an SPI ICSP Micro SD Card Adapter for data storage, and a 9V rechargeable battery for power supply, as shown in Fig. 2. The ADXL 335 is a tri-axial accelerometer which is capable of measuring vibrations along the X, Y, and Z axes. This combination of components were selected to ensure that the package is small, light, and can be easily fitted onto the handlebar, frame, or any other suitable position on the bicycle that can effectively capture the vibrations generated as the bicycle travels on both smooth and bumpy pavements. In this experiment, the bicycle speed will be monitored using an app installed on a smartphone. Figure 2 shows the Accelerometer Sensor Package together with its components whereas Fig. 3 shows the placement of the ASP and smartphone on the handlebar of the bicycle.

Although the ADXL 335 MEMS accelerometer is capable of measuring vibrations along the X, Y, and Z axes, in this study we are primarily concerned with the vibrations generated along the Z axis since the vibrations recorded along the Z axis correspond to vertical vibrations of the bicycle as the bicycle is traveling along the pavement which corresponds to the degree of smoothness of the pavement. The sampling rate of the Arduino Nano microcontroller is set at 50 samples per second. This selected sampling rate adheres to the Nyquist criteria in order to prevent signal aliasing.

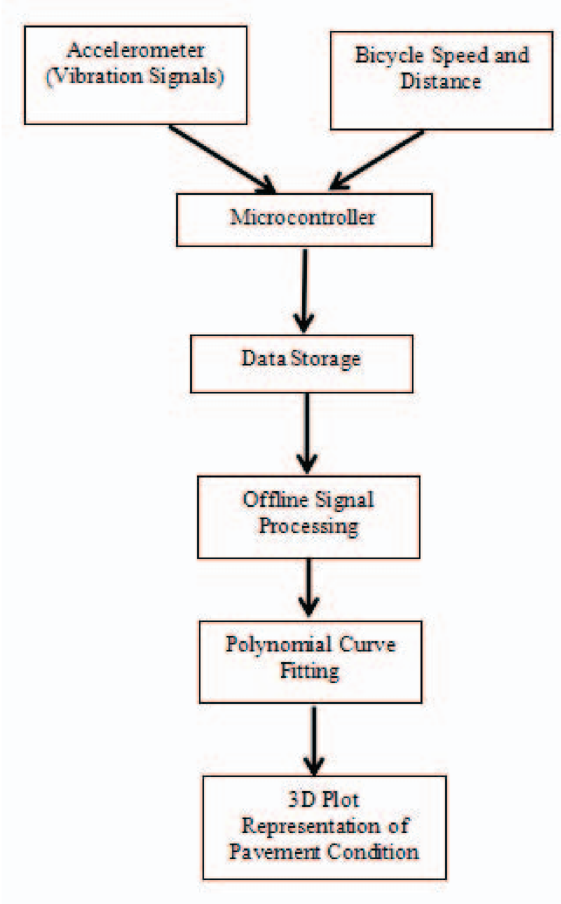

Fig. 1: Block diagram of the proposed methodology for pavement condition monitoring.

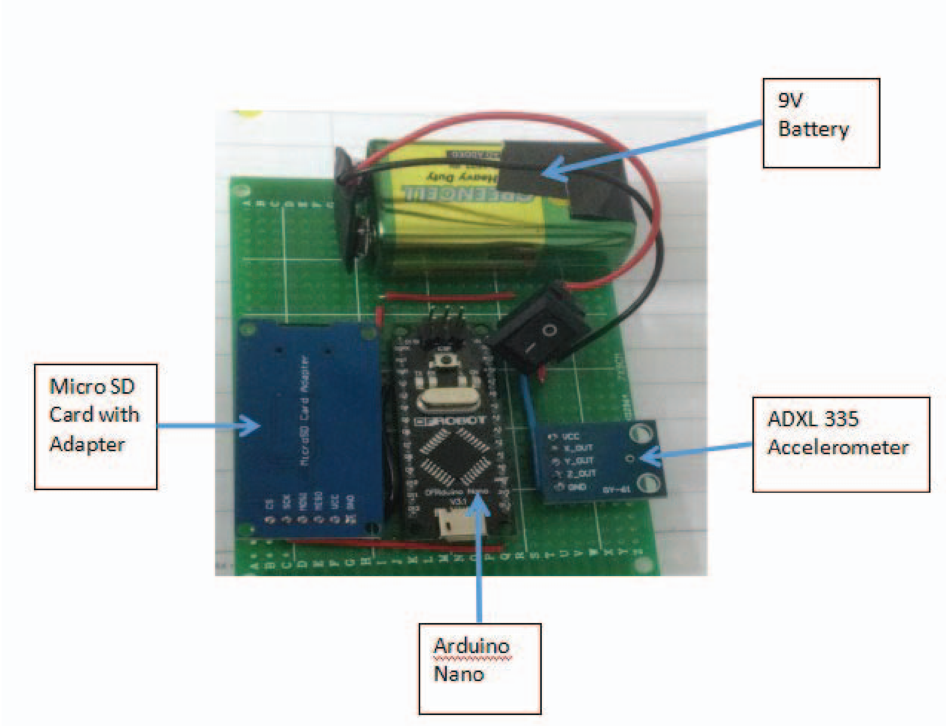


Fig. 2: Accelerometer sensor package.

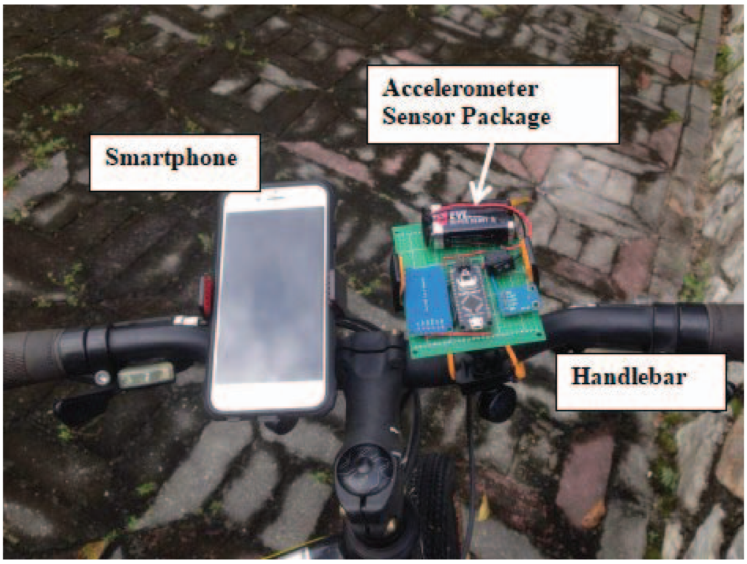


Fig. 3: Accelerometer Sensor Package and smartphone placement on bicycle handlebar.

### *3.1.2 Vibration Data Collection*

In this study, pavements located on two separate cycling routes were chosen for the vibration data measurement and analysis. The first cycling route consists of a smooth pavement, as shown in Fig. 4 (left), whereas the second cycling route consists of an uneven pavement with irregularities due to branching roots from a nearby tree, as shown in Fig. 4 (right). The distance travelled by the bicycle on both routes was set to 50 meters. The width of the road was 1.5 meters.

In this study, we are primarily concerned with the acceleration data recorded along the vertical Z axis since this data best reflects the pavement condition. Accelerometer data from the X and Y coordinates are discarded in this study. During the bicycle ride in each region, the speed of the bicycle was fixed at 5km/h and the distance travelled was 45 meters. An app installed on the smartphone was used to keep track of the speed of the bicycle and also of the distanced travelled by the cyclist. Fig. 5 shows the pavement that has been divided into 10 regions. Each region will be traversed by the bicycle and data corresponding to the overall pavement condition in each region has been collected.

Fig. 4: Smooth pavement (left) and uneven pavement with irregularities (right).

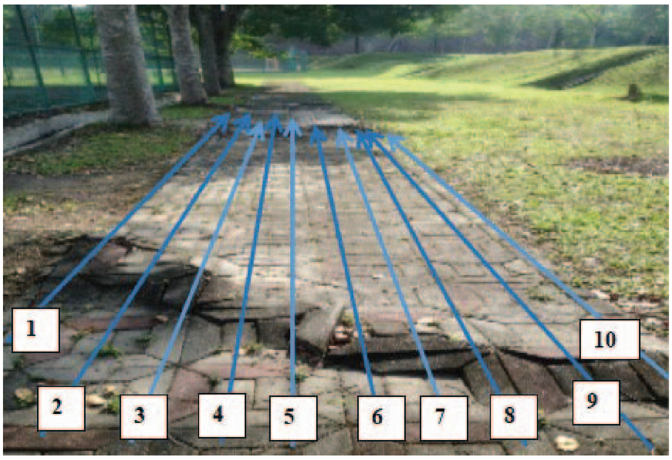


Fig. 5: Division of pavement into 10 regions which will be traversed by the bicycle.

### 3.2 Signal Processing

In order to extract meaningful information regarding the condition of the pavement in each of these 10 regions traversed by the bicycle from the accelerometer data, the raw accelerometer data needs to be processed in order to reveal the presence of significant irregularities on the pavement such as potholes and bumps and also the severity of the irregularity. For example deeper potholes or higher bumps on the pavement will result in higher amplitudes of the accelerometer data collected. This is one of the advantages of analyzing the condition of the pavement with accelerometer data compared to computer vision based methods. Computer vision based methods are able to accurately detect the location of a road anomaly whatever the depth or severity but the irregularity cannot be fully captured and analyzed using computer vision based methods alone [6-10].

### *3.2.1 Envelope Detection*

The accelerometer data collected from each of the regions (Region 1 to Region 10) reflects the condition of the pavement, as shown in Fig. 6 to Fig. 10. All the raw data have been full wave rectified to eliminate all the negative values in the results. In this paper an envelope detection method that consists of a combination of calculating the absolute value of the raw accelerometer data (full wave rectification) combined with low pass filtering with a very low cut off frequency is implemented to obtain an envelope of the raw accelerometer data. The amplitude of the enveloped signal is a representation of the severity of the irregularity. A low pass filter was designed in order to complete the envelope detector design. Figure 11 shows the magnitude response for a 51st order FIR low pass filter with a cut off frequency of 13 Hz that was used for the envelope detection method and was designed using the Matlab filter design toolbox.

### *3.2.2 Offset Correction*

Before envelope detection is performed, another preprocessing method known as offset correction is required. Offset correction is required since the accelerometer is highly sensitive even to minute variations in the evenness of the pavement, which are insignificant to our analysis and do not correspond to significant irregularities of the pavement such as bumps and potholes. Therefore, baseline accelerometer measurements are required. Baseline measurements are obtained by logging accelerometer measurements while the bicycle is travelling on a smooth pavement with no significant irregularities. The accelerometer data obtained by any other accelerometer measurement will then be subtracted with the average of the baseline measurements resulting in offset correction. Offset correction ensures that insignificant accelerometer readings that represent minute variations in the pavement are discarded from the analysis of the pavement condition. From test rides conducted on a smooth road, it was found that the highest signal amplitude is 0.2 $m/s^2$. Therefore, all collected data will be subtracted by this value resulting in the offset corrected results shown in Fig. 12 to Fig. 14. The offset corrected data gives a better indication of which parts of the pavement contain significant irregularities such as potholes and bumps.

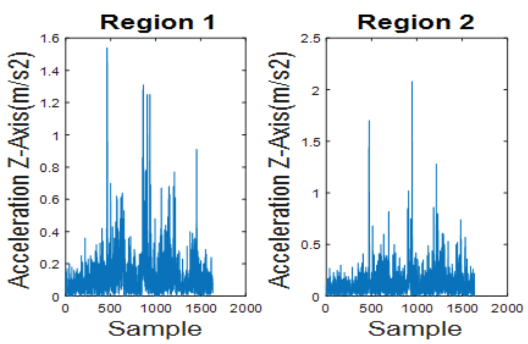


Fig. 6: Rectified accelerometer data for regions 1-2.

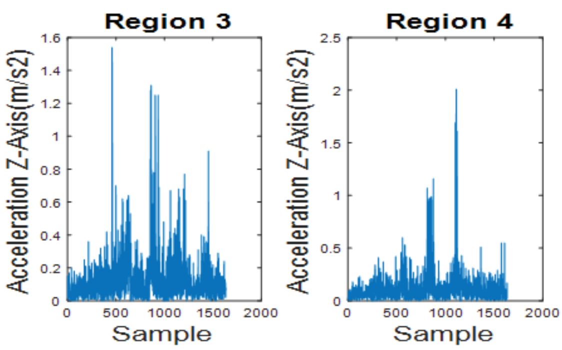


Fig. 7: Rectified accelerometer data for regions 3-4.

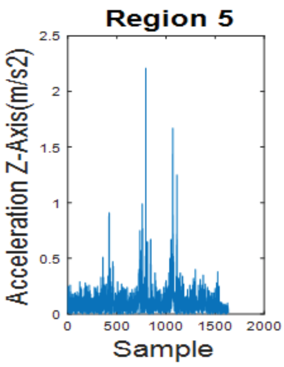


Fig. 8: Rectified accelerometer data for regions 5-6.

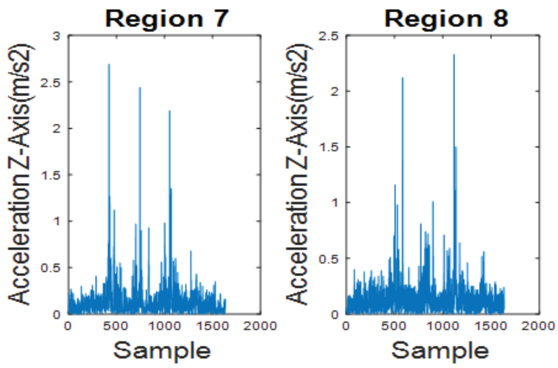


Fig. 9: Rectified accelerometer data for regions 7-8.

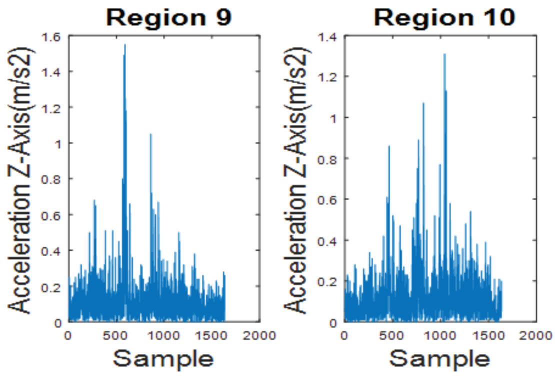


Fig. 10: Rectified accelerometer data for regions 9-10.

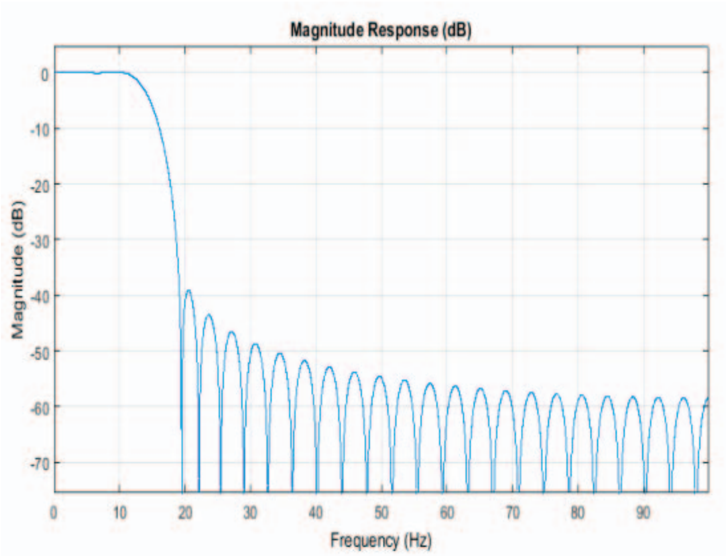


Fig. 11: Magnitude response of FIR low pass filter used for envelope detection.

https://doi.org/10.31436/iiumej.v21i1.1223

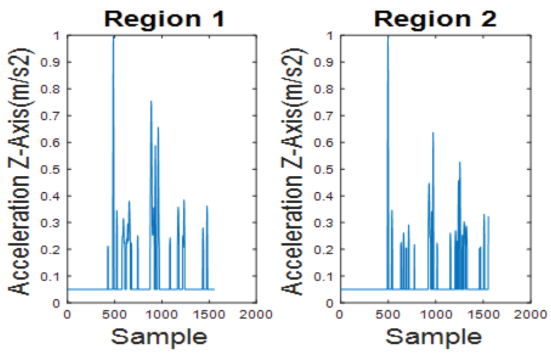


Fig. 12: Offset corrected accelerometer data for regions 1-2.

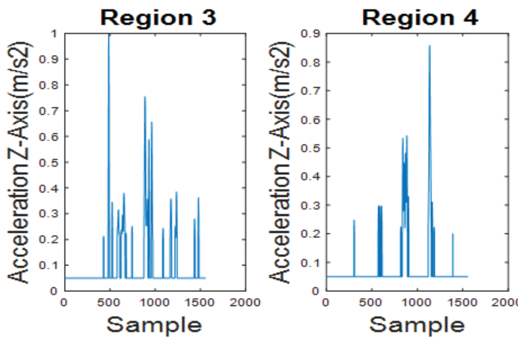


Fig. 13: Offset corrected accelerometer data for regions 3-4.

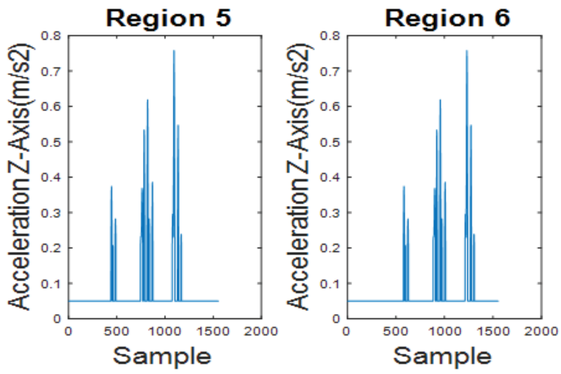


Fig. 14: Offset corrected accelerometer data for regions 5-6.

### *3.2.3 Polynomial Curve Fitting*

Polynomial curve fitting can be utilized in order to obtain a mathematical polynomial model that represents the condition of the pavement at each of the regions from 1 to 10. Polynomial curve fitting has been applied to all of the data presented in Fig. 6 to Fig. 8 resulting in polynomial functions that reflect the condition of the pavement. The polynomial functions that correspond to each of the regions are represented by $Y_1(s)$ to $Y_{10}(s)$ as shown below.

$$Y_1(s) = 0.00000015s^{60} \cdots - 0.0003s^2 + 0.0033s - 0.357 \quad (1)$$

$$Y_2(s) = 0.00000021s^{60} \cdots - 0.001s^2 + 0.0103s + 0.0274 \quad (2)$$

$$Y_3(s) = 0.00000011s^{60} \cdots - 0.0003s^2 + 0.0033s + 0.0357 \quad (3)$$

$$Y_4(s) = 0.00000001s^{60} \cdots - 0.001s^2 + 0.0155s - 0.0363 \quad (4)$$

$$Y_5(s) = 0.00000005s^{60} \cdots - 0.0001s^2 - 0.0053s + 0.0907 \quad (5)$$

$$Y_6(s) = 0.00000003s^{60} \cdots + 0.0009s^2 - 0.0134s + 0.1167 \quad (6)$$

$$Y_7(s) = 0.00000009s^{60} \cdots + 0.0011s^2 - 0.0185s - 0.1516 \quad (7)$$

$$Y_8(s) = 0.00000005s^{60} \cdots + -0.0003s^2 + 0.0056s + 0.0189 \quad (8)$$

$$Y_9(s) = 0.00000004s^{60} \cdots + 0.0018s^2 - 0.0287s + 0.1963 \quad (9)$$

$$Y_{10}(s) = 0.00000008s^{60} \cdots + 0.0004s^2 + 0.0036s + 0.0455 \quad (10)$$

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Figure 15 shows the rectified and offset corrected accelerometer data from Region 5, together with the graph of the polynomial approximation function of this data. From these graphs it becomes apparent that there are three significant irregularities of the road that could be due to uneven surfaces due to branching roots, potholes, or other road/pavement construction factors such as uneven bricks. Upon obtaining the polynomial approximation together with prior knowledge of the speed of the bicycle, the sampling rate used for the accelerometer data collection, and the distance of the road, we can determine the location of the irregularity and subsequently manpower and resources can be effectively utilized for the pavement/road repair works. Finally, the processed accelerometer data, either by envelope detection or polynomial approximation, can be extrapolated and combined to form a 3D plot that is an overall representation of the condition of the pavement, as shown in Fig. 16 and Fig. 17.

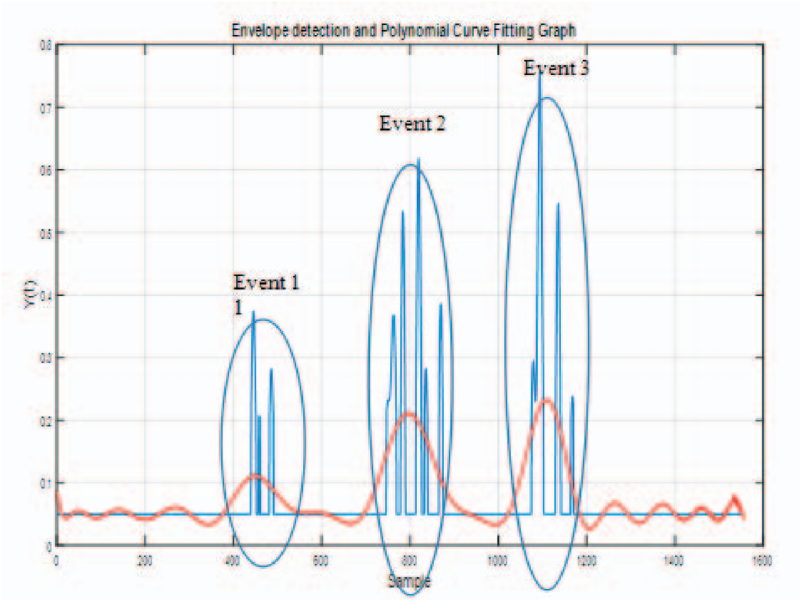


Fig. 15: Processed accelerometer data indicating 3 pavement irregularities together with corresponding polynomial approximation.

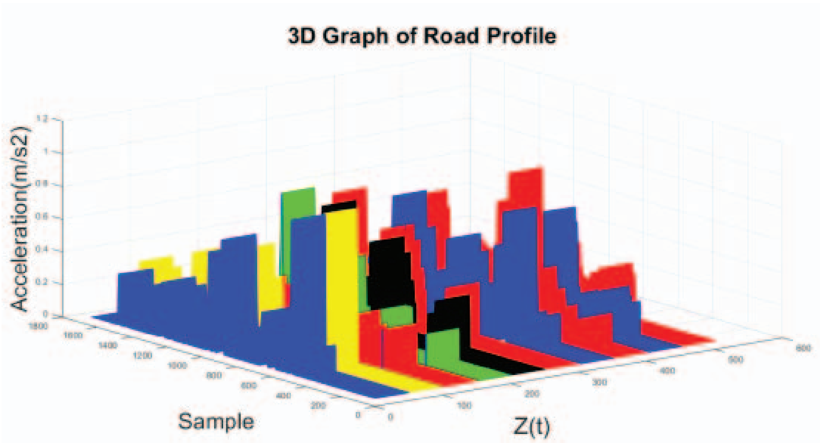


Fig. 16: 3D plot of pavement condition - extrapolated envelope detection data.

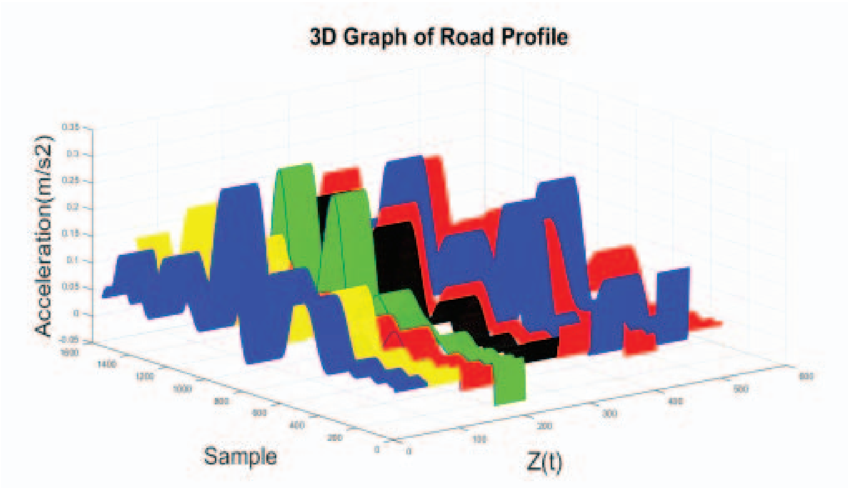


Fig. 17: 3D plot of pavement condition - extrapolated polynomial approximation data.

## 4. CONCLUSION

In conclusion, a method for obtaining mathematical models that represent the overall pavement conditions has been proposed using bicycle-mounted accelerometer data. The proposed method based on accelerometer data is advantageous compared to image processing methods since the severity of the irregularity can be effectively captured by accelerometers. For future work, the proposed technique can be further extended by placing Accelerometer Sensor Packages on multiple bicycles or vehicles that are traversing the same route. Each Accelerometer Sensor Package can be equipped with an antenna to send the collected data to a gateway resulting in a complete Internet of Things (IOT) application.

## ACKNOWLEDGEMENT

The authors would like to thank the Ministry of Education Malaysia for funding this research project under the Fundamental Research Grant Scheme - Grant No: FRGS19-057-0665 and FRGS16-053-0552 and also the International Islamic University Malaysia for funding this research under the Research Initiative Grant Scheme - Grant No: RIGS17-152-0727.

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