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6 authors, including:

Habeeb Bello Salau
Ahmadu Bello University

Adeiza James Onumanyi
Federal University of Technology Minna

A. M. Aibinu
Federal University of Technology Minna

Liz Onwuka
Federal University of Technology Minna

A Survey of Accelerometer-Based Techniques for Road Anomalies Detection and Characterization

[1]H. Bello-Salau*, [2]A. J. Onumanyi, [3]A. M. Aibinu, [2]E. N. Onwuka, [4]J. J. Dukiya and [5]H. Ohize

[1] Department of Computer Engineering, Ahmadu Bello University Zaria, Nigeria

[2]Department of Telecommunication Engineering, [3] Department of Mechatronics Engineering, [4]Department of Transport Management, [5]Department of Electrical/Electronic Engineering,

[2,3,4,5]Federal University of Technology, P.M.B. 65, Minna, Niger State, Nigeria.

*Corresponding Author's Email: bellosalau@gmail.com

Abstract- *In this paper, we present a decade survey of accelerometer-based sensor approaches proposed in the literature for road surface condition monitoring and anomaly detection. The main objective is to evaluate the performance of different documented accelerometer-based road anomaly detection techniques proposed in the literature, towards identifying their various strengths and weaknesses. We observed that a major challenge associated with these approaches lies in the detection of road anomalies and characterizing these anomalies into either potholes or speed bumps directly from the irregularly fluctuating measured signals from an accelerometer. This drawback limits the efficacy of many proposed variants of accelerometer sensor based approaches when used for road condition monitoring. Thus, future investigations will factor these in the design process towards aiding the choice of favourable techniques for future vehicle deployments by vehicle technology developers, as well as improvement for future unmanned vehicles. Furthermore, several open research issues that need to be addressed in designing and developing robust accelerometer based road monitoring systems are highlighted.*

Keywords: Accelerometer, Anomaly, Bumps, Characterization, Potholes, Road and Smartphone

1. Introduction

Road anomaly is referred to as any deviation or variation from the standard road surface conditions [1-3]. This anomaly can be noticed in forms of potholes, rutting, cracks and speed-bumps. These anomalies inhibit the free flow of traffic[4]. We note that, the most prevalent types of anomalies found on Nigeria road and around the world are the speed-bumps and potholes. These two types of anomalies have been identified as one of the major causes of road accidents leading to loss of lives and properties as well as discomfort experienced while driving and vehicle damages [4-6]. The used of substandard materials for road construction, poor drainage system, lack of compliance with acceptable speed-bumps construction guideline, proper road signage as well as poor maintenance culture has been reported as factors causing these road anomalies [4, 7-9]. The lack of prior knowledge of these anomalies by drivers often times resulted in drivers running into them or even losing control while attempting to avoid them, thereby leading to accident.

A possible solution of reducing these anomalies induced road accident is to equip vehicle with the capabilities of detecting, characterizing and profiling the road anomalies. This will enable drivers to have prior knowledge of the presence and location of this anomalies. Hence, providing opportunity for appropriate decisions making by driver while driving, such decisions could be to either completely slowdown if the anomaly is speed-bumps or swerve away if it is pothole. In detecting these anomalies, a widely used and reported approach in literature is accelerometer sensors for measuring vehicles vibration relative to g-force while driving on asphalt road surface. The popularity of the accelerometer sensor for road conditions monitoring is attributed to its potential for reliable anomaly detection, its versatility, ease of deployment and adaptability to mobile phones [8, 10]. The measured signal by the accelerometer sensor can then be processed using various processing techniques towards the localization of portion of the signals with road anomalies and characterizing the anomalies into potholes or speed-bumps.

Consequently, this paper presents a decade survey of various state of 80 the art approaches proposed in literature for road anomalies detection and characterization. The strengths and weaknesses of the various approaches deployed by different authors were evaluated. The peculiar challenge of processing the irregularly fluctuating signals with noise measured by the accelerometer sensor towards detecting and characterizing portion with anomaly is examined. Open research challenges that need to be addressed towards the development of a robust accelerometer-based road surface conditions monitoring system are highlighted. This decade survey paper differs from other similar reviews because

i. The focus of the review in [9] was on describing the various types of pavement roads, the possible types of defects that can be found on the road surface as well as the applications of remote sensing for defects detection. While, in this paper the focus is on reviewing different accelerometer-based approaches and processing techniques for anomaly detection and characterization.
ii. The survey in [11] is limited in scope as emphasis was not on the processing techniques, while that in [12] focused on the use of accelerometer sensor in measuring human physical activities such as motion and not on road anomaly detection as comprehensively examined in this paper.

The rest of the paper is organized as follows: Section 2 presents an overview of the accelerometer sensor devices. Various techniques used for post-processing and analysis of the measured signals by the accelerometer device is presented in Section 3. Survey of different accelerometer embedded based approaches for road surface condition monitoring is presented in Section 4. While, conclusion and suggestion for future research direction is provided in Section 5.

2. Overview of Accelerometer Sensor Devices

In the last decade, several research efforts based on the use of accelerometer devices for road surface condition monitoring has been proposed in literature with the intent for vehicle adaptation. An overview of the accelerometer device is succinctly described here.

An accelerometer is an electromechanical device design for measuring proper acceleration also called g-force [13, 14]. This measured physical acceleration due to g-force is represented as an electrical signal. We note that most times the accelerometer sensor are embedded on other devices such as the National Instrument MyRio data acquisition board shown in Figure 1, or even on Smartphones. Though, it can also sometimes be a standalone component.

There are several types of accelerometer sensors classified based on the technology used for their productions [13, 14]. These include the piezoelectric accelerometer that converts the output of a mass voltage to acceleration, piezoresistive accelerometer that uses the change in resistance in measuring acceleration while those that uses the changed in capacitance for measuring acceleration are called capacitive accelerometer. The Hall effect accelerometer is designed based on the changes in sensed magnetic field that are converted into an electrical signal while that due to changes in the resistivity of material due to magnetic field are called Magneto-resistive accelerometer. Generally, most accelerometers are made of capacitive plate. Some of these plates were fixed while others were attached to a spring. An internal displacement is experienced by the spring when the sensors

Figure 1: Image of Accelerometer Embedded in MyRio Device

is acted upon by g-force [13]. The resultant changes in the movement of the plate in relation to each other determined acceleration. Summarily, an accelerometer can be described as a transducer that converts mechanical stress or other forms of energy into an electrical signal [14]. A typical 3-dimensional accelerometer axis is shown in Figure 2 with each axis

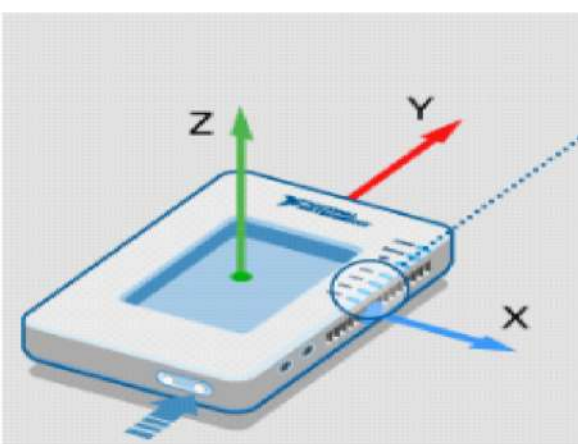

Figure 2: A Typical Accelerometer 3 D-Axis

monitoring a specific activity of the vehicle. The X-axis monitors the turning left and right of vehicle, Y-axis monitors the slope on the road while the upward and downward movement of vehicles are measured by the Z-axis which is mostly used for road anomaly detection. The corresponding measured sample signals by each of the accelerometer axis when used for road anomaly measurement is shown in Figure 3 [15].

Accelerometer has found applications in many engineering fields among which include its used in digital cameras and computers for upright display of images [16], in aviation's industry for stabilization of drones [17, 18], for vehicle airbags deployment and crash detection [19, 20] and recently for road anomaly detection [2, 21-24]. Though the focus of this survey paper is on its used for road surface

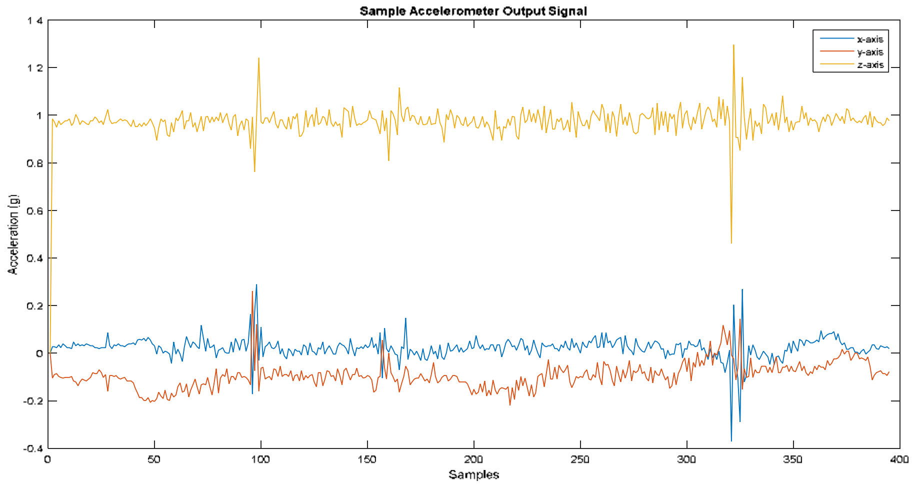

Figure 3: Sample Measured Road Surface Conditions Signals for each of the Accelerometer 3-D Axis

condition monitoring and anomaly detection.

3. Techniques used for Post-Processing and Analysis of the Measured Signals by Accelerometer Devices Towards Road Anomaly Detection

Various techniques have been presented in literature for processing the acquired road surface conditions signals towards detecting portions with anomaly. These technique for processing the measured signals by accelerometer are mainly categorized into three. Namely, Statistical analysis-based approach, Machine learning based approach and Time-Frequency analysis-based approach as examined in the following subsections.

3.1. Statistical Analysis based Approach

Several proposed approaches in the literature for road surface condition monitoring such as [2, 8, 23-26] uses this technique to either determine the type of road surface on which the road surface conditions data is being acquired (smooth or rough road surface) or to either process the acquired data towards detecting portions with anomaly. We note that of particular importance is the z-axis measured acceleration. This is because it monitors the upward and downward movement of the vehicles vibration, which can be used to detect road anomalies. Statistical measure such as the mean, standard deviation, variance, z-difference and energy of the measured z-axis acceleration signal were usually computed using MATLAB. Portions of the signal with anomaly usually have high deviation from the mean and used for anomaly detection. The average value of the measured acceleration signal μ known as the mean were usually computed using (1). The standard deviation, σ, which is a measure of how far the measured discrete-time signal fluctuates around the mean, were computed using (2).

$$\mu = \frac{1}{N}\sum_{i=0}^{N-1} x_i \tag{1}$$

$$\sigma = \left(\frac{1}{N}\sum_{i=0}^{N-1}\left(x_i - \mu\right)^2\right)^{\frac{1}{2}} \tag{2}$$

where, N is the interval width, x_i is the sample z-axis vertical acceleration for $i = 0,1,2,...N-1$. σ is the standard deviation and μ is the mean. The energy content E of the measured acceleration signal, x_i for $i = 0,1,2,...N-1$, were usually computed using (3). This were used to detect portions of the measured acceleration signals with road anomaly, because portion with anomalies have higher energy content compared to other anomaly free portions [8, 24]. We note that, threshold values were often manually set in order to identify portions of higher energy content, and hence, indicating the presence of possible road anomalies within the measured acceleration signal.

$$E = \sum_{i=0}^{N-1}\left(\left|x_i\right|\right)^2 \tag{3}$$

3.2. Machine Learning based approach

This road surface condition data post-processing technique entails the use of a machine learning approach such as Artificial Neural Network (ANN), Support Vector Machine (SVM) and so on, for road anomaly detection from measured acceleration signal. Signal features were usually extracted from the measured acceleration signal and used in training, testing and validation of the results obtained using the machine learning approach towards detection and classification of road anomaly. This extracted features often times include the mean and standard deviation expressed in 1 and 2 respectively. Further details on the use of this approach can be found in [1, 10, 27-31].

3.3. Time-Frequency Analysis based Approach

A Fast Fourier Transform (FFT) algorithm is another popular processing technique that has been used in literatures for processing the measured acceleration signals, towards road anomaly detection. Usually the FFT was used in computing the Discrete Fourier Transform (DFT) using (4). The computed DFT were used in analysing the measured acceleration signal in frequency domain. The vibrational strength of the measured acceleration signal in each frequency window were assumed to be the sum total of the magnitude of the FFT, which were used to extract features and relationship between the measured acceleration and the road roughness condition. Further details on the use of this approach for road anomaly detection can be found in [28, 32, 33].

$$x\left(k\right) = \sum_{i=0}^{N-1} x_i e^{-j2\pi k_i/N} \tag{4}$$

where, $x(k)$ is the DFT of the sample vertical acceleration x_i for $i,k = 0,1,2,...N-1$.

4. Survey of Different Accelerometer Embedded Approaches for Road Surface Condition Monitoring

In 2007, a sensor network-based approach that incorporates an accelerometer sensor in its design referred to as BusNet was proposed for monitoring road surface conditions and environmental pollution in [34]. The developed system was installed on public transport buses for monitoring road surface conditions as they go about their daily activities. The acquired road surface conditions data were transmitted wirelessly to a substation located at each bus terminal. The received data at each bus stations are transmitted to the main station with the aid of some substations which serves as routers for onward processing and analysis. The proposed approach has the merit of utilizing few numbers of moving sensors for road surface conditions monitoring. Thereby, saving the cost of deployment of large number of sensors mote. Nevertheless, the developed system can only withstand a few hours of latency. Also, it has low probability of anomaly detection with high false alarm rate. In addition, characterizing the detected road anomalies into potholes or bumps was not examined.

An approach based on accelerometer and GPS sensor embedded on Smartphone as well as microphone was proposed in [27] for road traffic monitoring and anomalies detection. A virtual reorientation of the phone accelerometer used for measuring acceleration signal during drive test was performed in order to localize the Smartphone in an energy efficient manner. Honking during drive test was sensed using the microphone audio sound output, while the corresponding portions of the sensed signal with anomalies are logged using a GPS sensor. Experimental results show that the proposed approach was able to effectively detect road anomalies and traffic conditions. However, it was unable to characterize the detected anomalies into potholes or speed bumps. Furthermore, analysis of the severity of the detected road anomalies in terms of depth and width, that are crucial in informing and adapting drivers driving process were not considered. In addition, the use of the manual static threshold approach which may not be the optimal threshold value can affect the efficacy of the proposed system.

A pothole patrol system was developed for anomaly detection in [31]. The developed system comprises of a vehicle equipped with a mobile and accelerometer sensor for monitoring and detecting potholes. The accelerometer data reading captured during drive test was relayed via WiFi to a central database. This data was used for training the support vector machine that clustered the data based on the presence or absence of potholes. The developed approach was able to accurately detect potholes and other road anomalies from the logged vehicle vibration data. However, the used of machine learning that required training, testing and validation before it could be used for the characterization of detected road anomalies makes it complex.

A tri-axial accelerometer sensor embedded on Smartphone was used for road surface conditions monitoring while riding on a motorcycle in [28]. The approach entails using a support vector machine (SVM) for processing the measured acceleration by detecting road anomalies as well as their corresponding GPS coordinates while an unsupervised machine learning was used in training and setting threshold value for clustering the measured acceleration signal. The propose system provides cheap and effective way of road surface conditions monitoring. Nevertheless, it remains pertinent to evaluate the performance of the system using higher sampling rates above 25 Hz to arrive at better working conditions. Furthermore, the accuracy of the reported results depends on sensitivity of the accelerometer sensor embedded on the smartphones used during drive test. In addition, the detection and characterization of road anomaly using the SVM machine makes the proposed system complex. Thus, the need for direct detection and characterization of anomalies from the measured acceleration signal.

A mobile phone accelerometer based real time pothole anomaly detection system was presented in [35]. The measured vertical acceleration signal (Z-axis) was analysed using some statistical parameters like the Z-thresh, Z-diff and Z-peak in detecting portions of the signals with road anomalies. Anomaly is detected using the Z-thresh when the measured acceleration at any points in the signal exceeds a pre-set threshold value. The value between two consecutive Z-axis measurements were computed using the Z-diff and compared with a pre-set threshold value for pothole anomaly detection alongside the peak acceleration recorded along the vertical axis referred to as Z-peak. The post processing of the measured signal was done by computing the standard deviation of the z-axis acceleration using (3). Furthermore, G-ZERO was used for detecting measurement tuples when vehicle was temporarily in free fall, at which point the measured acceleration was close to zero relative to g-force (0g). The proposed approach was able to accurately detect potholes with high probability of detection of about 90%. However, a major drawback with the proposed system was the use of a manual threshold that cannot adapt automatically to the irregularly fluctuating noise floor of the measured vertical acceleration signals. Furthermore, the accuracy of the proposed approach depends on the sensitivity of the type of android operating system on which the accelerometer device was embedded on. Thus, making the proposed system vendor specific, as output results may vary across different platforms. In addition, characterization of detected road anomalies into potholes and bumps directly from the measured signals was not examined. An approach for road surface conditions monitoring and anomaly detection based on a 3-dimensional mobile phone accelerometer sensor and GPS coordinates was proposed in [29]. The proposed system comprises of three stages namely, pre-processing, classification and visualization. The measured acceleration by the accelerometer embedded on mobile phone (Nokia N98 8GB) were collected by a program written in java at a sampling frequency of 38Hz and GPS reading at 1Hz. Statistical parameters namely the mean and standard deviation shown in (1) and (2) respectively, were used for features extraction towards detecting road anomaly. Also, DFT presented in (4) was used to extract features for anomaly detection. The extracted features were used to trained and evaluate the support vector machine used for classification and detection. Results obtained showed an improved performance when compared to other similar approaches in the literature [27, 31]. The pre-processing of the measured acceleration and GPS signals for speed estimation reduced sampling errors thereby aiding improved performance noticed when compared to that developed by [27, 31]. However, difficulty was encountered in clustering data from multiple drivers which affected the performance of the developed system. Also, unsatisfactory speed estimates were observed in the experimental results irrespective of how the other was tuned. Furthermore, the characterization of the detected road anomalies into potholes or bumps was not examined. In addition, the model and type of mobile phone on which the accelerometer sensor is embedded on affects the accuracy of the proposed system due to their varying sensitivity.

An accelerometer sensor and GPS data logger embedded on mobile phone was used for pavement anomalies monitoring in [36]. It measures the vertical axis acceleration and their corresponding GPS coordinates during drive test towards detecting road anomaly. Different placement of the mobile phones inside the experimental vehicle during drive test was investigated. It was reported that placing the mobile phone on the dashboard gives lower magnitude signal response compared to placing it inside the driver's pocket. Furthermore, road anomalies were detected from the measured acceleration signal based on a pre-set threshold value. The signal's power of the measured signal was computed and continuously averaged as it exceeded the set threshold of the normal acceleration until a GPS receiver sends the new location. This was then sent to the software communication module which logged the data to a central server. Experimental results showed that the developed system was able to detect road anomalies and suitable for quantitative assessment of pavement surfaces. Nevertheless, the anomaly detection accuracy depends on sensitivity of the mobile phone used for data acquisition. Also, the used of a pre-set manual threshold value may affects the accuracy of the proposed system, as it cannot adapt to the frequently changing noise floor of the measured acceleration signal. Furthermore, characterizing the detected road anomaly into potholes or speed bumps directly from the measured acceleration signal was not examined. An investigative approach for road surface conditions monitoring based on accelerometer sensors embedded on smartphones was proposed in [37]. The accelerometer embedded smartphones were placed on the dashboard of experimental vehicles for measuring acceleration signals during drive test. The measured signals were processed using some statistical parameters, namely standard deviation, Z-thresh, G-zero, Z-diff and simple thresholding discussed in section 3 towards road anomaly detection. Experimental results showed the feasibility of using accelerometer sensors embedded on different smartphones for road surface conditions monitoring. Though, variations were observed in measured signals using different Smartphones, despite having the same accelerometer sensors application installed on each phone. This further supports the assertion that different phone platforms produce different measured signal output, which could generate conflicting conclusions, and false alarms. In addition, the proposed approach was unable to characterize the detected road anomalies into potholes or bumps. An approach for road anomaly monitoring using a customized dedicated embedded accelerometer sensors and microphones referred to as carmote was proposed in [38]. This entails a hardware design comprising of a microcontroller unit (TI MCU MSP430F1611), a TMote mini wireless sensor network module, CC2420 chipcon transceiver, ST EEPROM M25P80 chip and a BCM9765P-44 electret microphone attached to the main microcontroller board. An IDG500 dual-axis gyroscope ADXL335 and accelerometer was embedded on the main microcontroller board to measure acceleration along 3-dimensional axis namely, x, y and z-axis as well as Fastrax IT300 GPS module to logged corresponding GPS coordinates of measured acceleration. A detachable Wi-Fi communication board consisting of RN-131C network board was attached to the main board for communicating the sensed anomaly to a central server for processing. Experimental results showed that the measured acceleration using the developed CarMote gives similar results when compared to that acquired using an accelerometer sensor embedded on HTC android smartphone. Also, the sensitivity of the measured acceleration using CarMote does not depends on any smartphone as it was a dedicated embedded system developed for road monitoring. However, processing the measured acceleration during drive test towards detecting portion with road anomalies as well as characterization of the detected anomaly into pothole or bump was not examined.

A mobile phone accelerometer-based application called UNIquALroad that allows the use of piggybacked sensors was developed for road anomaly detections, specifically potholes and speed bumps in [25]. The developed application was installed on four different smartphones and a tablet. These phones were positioned at different locations in the experimental vehicle for data acquisition during drive test. A Global Positioning System (GPS) was used in tracking the locations of road anomalies. An algorithm was developed for processing the acquired signal towards detecting portions with road anomaly based on its energy content. The original signal was passed through three different filters to reduce the noise components presents in the signal. Euler angle was used to re-orientate the measured acceleration along the vertical axis that was further processed by the proposed algorithm to detects anomaly based on the energy content. The difference between the measured acceleration, signal energy and peak values were used for the detection of the two types of speed bumps considered in the work (stone bumps and rubber bumps). Results obtained showed that the developed approach successfully detected and distinguished between the two different types of speed bumps considered in the work as well as the best positioning of the mobile phone in the experimental vehicle. However, the performance of the developed system dropped during potholes detection with high level of misdetection. Also, there was no conclusive deduction on the best positioning of the mobile phone in the experimental vehicle during data acquisition. In addition, the characterization of the detected anomaly into potholes and speed bumps directly from the logged signal was not examined. Though, we noted that the peak event in the acquired signal was amplified during the free placement of mobile devices on the experimental vehicle. Furthermore, the proposed approach springs up some useful models and theoretical analysis capable of processing and computing different parameters for measured acceleration signals analysis. Interested readers are refer to [25] for more details.

A similar approach that entails the use of a 3-dimensional accelerometer-based sensor, GPS and a video module for road surface conditions monitoring was presented in [22]. An accelerometer sensor embedded on an iPad and shimmer (high frequency accelerometer) were used during drive test for data acquisition. The acquired information was made available to users using a Global Information System (GIS) platform. An onsite algorithm was designed for processing the acquired data towards detecting road anomaly in real-time. This has an advantage of reducing the volume of data saved or sent to the central server. Experimental results obtained shows the feasibility of using proposed system for road anomaly detection. Though characterizing the detected anomaly into potholes or speed bumps in order to aid driver's decision was not examined. In addition, the proposed system will be difficult to implement in areas with limited wireless connection for transmitting the acquired data to the central database, thereby leading to loss of some data.

An accelerometer embedded on smartphones was used in monitoring road roughness condition in [32]. An application called AndroSensor was installed on the smartphones and placed on dashboard of an experimental vehicle used for data acquisition. The same acceleration coordinates were assumed for the smartphones and the vehicle. The measured data by the accelerometer was analysed in frequency domain to extract features for road roughness evaluation. Some correlations were established between the extracted features and the road roughness conditions. These features were used to compute the road roughness index, that was used in classifying the road surface into good, fair, poor and bad. The measured acceleration was cross examined by the video images of the road surface captured by the camera mounted on the experimental vehicle for acquiring road surface condition images. Experimental results established a linear relationship between the road unevenness condition and the measured acceleration signal pattern. However, the assumption of fixed orientation coordinates of the smartphone and the vehicle acceleration is an unrealistic smartphone setting. Furthermore, detection and characterization of road anomaly from the measured road roughness index was not examined.

An architecture based on accelerometer embedded on smartphones for road defects detection was presented in [26]. This entails programming an accelerometer embedded on smartphones for measuring acceleration along the x, y and z vibrational axis with a sampling rate of 20 Hz. The measured acceleration was processed on board using statistical measures specifically mean and standard deviation presented in equation (1) and (3) respectively to detect portions with road anomalies. This computed statistical measure was used to determine the type of road surface on which the vehicle accelerations was measured. The filter proposed in [26] was used to removed noisy component from the measured z-axis signal in order to give an accurate estimation of portions with anomalies. The output of this filter was then passed into a low pass filter to improve the estimation of structure of the signal with anomaly. The proposed system has the advantage of small storage capacity requirement due to the onboard processing incorporated in the design. Results obtained shows an accurate detection of portion of the measured signal with road anomalies based on the filtered threshold signal approach. However, the proposed approach was unable to characterized the detected road anomalies into potholes or speed bumps.

The concept of participatory sensing approach was developed in [30]. An android application that measure acceleration along 3-dimensional axis and their corresponding GPS coordinates was designed and installed on smartphones for road surface conditions monitoring. The smartphones were placed in all experimental vehicles and used for measuring acceleration signals during drive test. The measured signals were processed and analyzed using a multi-layer perceptron machine learning approach, towards detection and classification of road anomalies into potholes, speed and metal bumps. Experimental results showed high accuracy level of road anomaly detection. Nevertheless, the used of the manual threshold approach for anomaly detection and classification as well as the high level of noise presents in the measured signal limits the effectiveness of the proposed approach.

Similarly, in 2014 an approach for monitoring drivers driving behaviour and road surface conditions based on an accelerometer sensor embedded on Smartphones was presented in [39]. The accelerometer measures vibration along the x, y, and z-xis at a sampling rate of 5 Hz and stored it in .txt format on the phone memory. Patterns were extracted from the measured vibration signal and thresholded based on pre-set values to detect the type of activities present in the signals as either, left or right turn, sudden braking, rough roads, potholes or speed bumps anomalies. Experimental results show that features for road anomalies detection were successfully extracted from the changing pattern of the z-axis vibration based on the signal deflection in either positive or negative direction with a corresponding slight deflection in both x and y-axis. However, the performance of the developed approach depends greatly on the type of smartphones on which the accelerometer sensor is embedded on and used for data acquisition. Furthermore, characterizing the detected anomalies into potholes or speed bumps directly from the measured acceleration signal by the accelerometer was not examined.

An automated sensing approach based on an accelerometer sensor was proposed in [24]. This approach measures acceleration along three-dimensional accelerometer axis and logged the measure data to a central database, which host an algorithm for processing the vertical acceleration (z-axis) measurement towards detecting portions of the signals with road anomalies. A manual threshold value was set based on experimental observations of the measured signal and used for thresholding the measured signal based on their computed energy content in detecting the presence of road anomalies. High detection accuracy was observed from the experimental results reported. Also, a linear relationship was established to exists between the acceleration impulse and road anomalies. Though, the need for reorienting the vertical acceleration axis using Euler angles makes the developed system complex. Furthermore, the manual threshold set for road anomalies detection may not be the optimal value, therefore there is need to automate the threshold setting. Furthermore, the accuracy of the developed system depends on the sensitivity of the Smartphone used for data acquisition. In addition, the characterization of the detected anomaly into potholes or bumps was not examined.

Similarly, a new methodology based on the use of accelerometer, GPS sensor and microphone embedded on a Smartphones for road anomalies monitoring was presented in [40]. These sensors were used to measure acceleration along three-dimensional axis (x, y and z-axis), as well as their corresponding coordinates and sound pressure. The vertical acceleration measured using the accelerometer was processed and used for road anomaly detection alongside the difference in sound level measured over time using a phonometer. This was achieved by comparing the measured data over a pre-set threshold value above which an anomaly is detected. The detected anomaly is logged in a road side infrastructure which could be appropriate authority. The proposed approach shows the feasibility of real time information and alertness of driver as well as management staff on road surface conditions. However, characterizing the detected anomaly into potholes or speed bumps was not considered. In addition, the used of the manual threshold value for detection may not be the optimal value, thus failing to adapt to the irregularly fluctuating noise floor of the measured acceleration.

An approach for road anomaly detection and drivers driving behaviour using an accelerometer sensor embedded on smartphones as well as its GPS sensor was proposed in [23]]. This entails measuring acceleration along 3-dimensional spatial axis namely, x, y and z-axis. Though of particular importance was the measured z-axis acceleration which was post processed towards detecting portion of the measured acceleration with anomaly. A fuzzy system was used for processing the measured acceleration based on some set rules towards detection and notification during unsafe driving. Results demonstrates the possibility of using the developed system for road anomaly detection. However, the proposed approach is computationally complex. Also, the accuracy of the results depends on the sensitivity of type of Smartphones on which the accelerometer sensor is embedded on.

A mobile phone accelerometer, gyroscope and inertial sensor were used for road surface conditions monitoring [1]. The effect of slope, drift and speed effects were catered for using an envelope method. A wavelength decomposition analysis was used to analysed the inertial sensor signal. Also, a support vector machine learning technique was used in classifying the detected road anomalies. Results obtained showed high levels of accuracy and detection rate. However, the severity of detected road anomalies was not examined. Furthermore, an attempt to characterize the detected road anomalies into potholes or speed bumps directly from the logged measured acceleration signal was not examined.

A mobile application for collaborative road surface condition monitoring was developed in [41]. The measured acceleration signal was processed by an android application developed and installed on the mobile device used for data acquisition. This was done towards extracting the roughness parameter presents in the measured signal. The indexes for the road roughness was estimated using a linear predictive coding. The proposed approach was able to detect road surface anomalies from measured acceleration signals. Nevertheless, the possibility of having different mobile phones running the android applications with varying sensitivity was not factored into their design. Thus, the accuracy of the developed system depends on the sensitivity of the mobile device running the application. Furthermore, characterization of the detected road anomaly into potholes or speed bumps was not examined.

An approach for monitoring road surface conditions based on an accelerometer sensor embedded on Smartphone was proposed in [26]. The measured acceleration signal was post processed using (1) which computes the signal average value and the deviation of the signal from the mean was also computed using (2). Inference from the computed standard deviation was used to determine the type of road surface on which the acceleration signal was measured. In detecting portions of the signal with road anomaly, a manual threshold value was determined and set. Measurement values above the set threshold was considered to be potholes anomaly, speed bumps or railway crossing. The developed system has the capability of recording the images of road with abnormal acceleration reading and send to a central database for processing. Also, it has low power consumption and costs due to small storage capacity requirement because of the onboard processing incorporated in the developed system. Furthermore, experimental results showed that the road anomalies were accurately detected using the filtered threshold signal approach. However, the developed approach was unable to differentiate between the various classes of road anomalies based on the measured 3-dimensional acceleration signature. An accelerometer sensor embedded on Nokia lumia 820 mobile device and a gyroscope framework was proposed by [21] for road surface conditions monitoring and anomaly detection. Features were extracted from the measured acceleration and used to train a support vector machine towards detection and characterization of detected road anomaly into potholes or speed bumps. Experimental results showed that the proposed approach was able to detect and classify road anomalies successfully. Nevertheless, it was observed that its accuracy depends largely on the sensitivity of the smartphone on which the accelerometer sensor is embedded on. Thus, making it vendor specific and difficult to generalize. Furthermore, characterization of the detected anomaly into potholes or speed bumps using machine learning opposed direct characterization from the measured acceleration signal makes the proposed technique complex.

The characterization of speed bumps using both theoretical modelling and acceleration measured using accelerometer sensor embedded on Smartphone was investigated in [42]. A mass, spring and damper system was used to model a quarter and half car, which was excited by some parameters similar to speed bumps in calculating its acceleration response. The theoretically computed acceleration measurement was compared to that obtained during physical measurement using accelerometer sensor embedded on Smartphone during drive test for validation purpose. The measured acceleration signal was converted into frequency domain using discrete Fourier transform in (4) and filtered using a low pass filter to remove the noise components from the signal. The acceleration pattern was extracted by averaging their absolute values using equation (1) over each second and scaled by the maximum value. Experimental results showed that the proposed approach was able to detect speed bumps and capable of monitoring road surface conditions thus reducing the cost of manual inspection of road surfaces. Also, features for detection of both single and multiple speed bumps were presented. Furthermore, memory space is maximized as only the compressed versions of the acquired signals were saved during data transmission. We observed that similar results were obtained for both the theoretical approach and the experimental approach using the precision accelerometer sensor embedded on Smartphone. However, there was no clear distinguishing features between single bump and multiple bumps that can be used for characterizing the detected speed bumps. Though, it was shown that both single and multiple bumps signal follow the same pattern. A similar approach for road anomaly detection and labelling based on theoretical modelling of a half car model using a Jump Diffusion Process (JDP) estimator in combination with a multi-input observer was proposed in [43].

The velocity disturbances at the two front wheels of vehicle were used as inputs to the developed half car model. These inputs were estimated using a multi-input observer that was presented in [44]. The JDP was used for estimating the system state towards implementing the input observer. Simulation result from the developed model shows a better performance when compared to that of Kalman filter. However, the proposed approach was computationally complex. Furthermore, there were no clear distinguishing feature that can be used for characterizing the detected road anomaly directly from the measured velocity of the vehicle.

An approach that involves the use of a multivariate genetic algorithm (GALGO) for road abnormalities detection based on measured data from a gyro, an accelerometer and GPS sensor connected to an IoT device was proposed in [45]. The measured data from the sensors were windowed for every two seconds, were statistical parameter that can characterised the whole datasets were extracted and used in training a genetic algorithm-based machine learning technique towards developing a logistic model for speed bumps detection. A total of about 14,090 data samples were collected during drive test over ten different laps at a speed of 20km/hr. Statistical parameters such as the mean, variance, skewness, kurtosis, standard deviation, dynamic range and maximum signal amplitude values was used in extracting features for the machine learning algorithm. A representative model was selected based on the frequency of appearance of a feature in the developed multivariate models using a forward selection and backward elimination strategy. Seventy percent of the datasets were used for training the system while, thirty percent were used for testing and validation. Though, the proposed approach was able to successfully detected speed bumps anomaly with a low false positive rate. But it is computationally complex as it requires the use of so many statistical features to be extracted for the machine learning. Furthermore, the system cannot detect other anomaly such as potholes, which is the most prevalent on most developing nations road and deadlier as usually no signage to signify the presence of such anomalies.

A similar approach based on support vector machine were some heuristic features reported in literature that uses accelerometer-based method for road anomaly detection were fused into a proposed support vector machine is presented in [46]. Focused was on performance comparison of most popular approaches based on either threshold or machine learning techniques for road anomaly detection as well as developing a web platform referred to as pothole lab for generating virtual roads and creating desired anomalies, which was a first step towards creating an avenue to obtained benchmark datasets. An extensive evaluation of the datasets was carried out by computing the sensitivity, precision and F1 score. For the proposed support vector machine approach presented in [46], twelve different statistical features were extracted during the pre-processing stage of the measured acceleration signals from each sliding windows. 30 different roads plagued with anomalies were generated from the pothole lab, which serve as testbed. To support the analysis, statistical test was carried out with the results obtained suggesting that the best performing approach was that of the STDEV(Z) proposed by [35, 38] among other similar and popular approaches reported in [31] and [27] considered for analysis. However, these approaches compared and evaluated as well as that proposed were only able to detect road anomalies without capable of characterising the detected anomalies into potholes or speed bumps. Similarly, in [47], a feature extraction method based on statistical and time domain analysis were used to extract pattern across each window for road anomaly descriptions and detections from measured acceleration datasets by a low-cost MEMS acceleration and GPS sensor embedded on tablet phone. Each monitored events were classified using a proposed decision tree classifier with a reported accuracy level of about 87%. However, the accuracy of the proposed approach depends largely on the type and make of the operating system on the tablet phone used for data acquisition.

5. Conclusion and Future Work

A decade review of road surface conditions monitoring systems using accelerometer-based devices has been presented. The desire to have future vehicles embedded with such intelligence towards the possibility of reducing anomaly induced accidents motivated the discussion herein. A look at different approaches particularly those based on smartphone implementations and dedicated hardware implementations was presented. Furthermore, an overview of the three major techniques for post processing the measured acceleration signal towards detecting portions with anomaly was provided. However, there are still several research issues to be addressed towards more robust accelerometer-based road surface monitoring systems. These include the need for more accurate techniques for detection and characterization of anomaly into potholes or speed bumps directly from the irregularly measured acceleration signals by the accelerometer, the need to automate the threshold system to reduce global errors, sensitivity examination and evaluation of accelerometers from different phone platforms. Other factors worth considering are evaluating the impact of varying sampling rate on the accuracy of the developed system, and examination of the severity of the detected road anomalies to help prioritize maintenance of roads. In essence, research in this subject matter is very much active, and the possibility of having commercially available improved accelerometer-based road monitoring systems for vehicles is closer than ever, which would ultimately lead to the reduction of road accidents.

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