ACCELEROMETER BASED ROAD DEFECTS IDENTIFICATION SYSTEM

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High precision accelerometers are now widely available thanks to the development of the MEMS technology. Especially embedded in smartphones and tablets, they became part of our daily life increasing the usability of our mobile electronic devices. Road defects assessment using 3D accelerometers is one of the great problems that can be tackled by employing large numbers of accelerometers mounted on vehicles. This paper proposes an architecture for an accelerometer based road defects identification system. The mathematical approach for road defect identification and the data aggregation methods are also discussed.

Keywords: pothole identification, 3D accelerometer, pothole clustering, mobile sensor network

1. Introduction

Small size sensors made possible a variety of applications in different fields of activity. Based on the information handling capabilities and compact size of the sensor nodes, sensor networks are often referred to as “smart dust” [1].

The variety of sensing capabilities offered by these devices also provides an opportunity to gain an unprecedented level of information about a target area, be it a room, building or outdoor. Wireless sensor networks (WSN) are fundamentally a tool to measure the spatial and temporal characteristics of any phenomena [2].

Embedding the accelerometer technology into the existing environmental sensors based motes, made possible a new wave of useful applications. From motion recognition [3] to localization [4] and even pothole identification [5], the accelerometers based applications offer a great amount of information.

Many drivers regard potholes as driving hazards and blame them not only for damaging their cars, but even for causing accidents. Bad roads also count for slower, more energy consuming and polluting traffic.

A prime concern of the current transport industry is the provision of sustainable transport through the improvement of efficiency, quality, safety and

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the reduction of the impact of energy use on the environment [6]. It is estimated that more than 30% of the accidents are caused by environmental conditions [7].

Therefore, in order to achieve a good environmental protection and to maintain a low accident rate, especially in large urban areas, keeping the road infrastructure in good working condition is a first major step forward.

The objectives of smart city related projects include implementing more environmental friendly technologies in our infrastructure that use less power and have a smaller environmental fingerprint. A road quality assessment system can be one of the backbones of such a system.

Less polluting vehicles are part of the solution and their popularity is growing, but they cannot offer an alternative solution at their present level of technological development. Therefore, the solution is to keep pollution as low as possible even while having the same kind of vehicle on our streets. A real life information system can keep drivers always aware about the road conditions ahead, helping them avoid congestions, badly maintained roads, thus resulting in a more fluid traffic, lower accident rates and less CO_2 emissions.

The major impediment is the vast area which needs to be subject to monitoring activities. Therefore, our solution involves employing mobile monitoring platforms equipped with accelerometer based road quality monitoring systems.

2. Related work

Using the latest available technologies, during the last decades, many studies have been conducted in order to find a working solution for automated road condition assessment. In order to perform the specific measuring and categorizing tasks, all the proposed solutions have in common a similar architecture based on sensors and a computing unit capable to process the data. In order to be easily deployed wherever it is needed, the monitoring system needs to be fit on a vehicle.

An automated solution is considered to be practical, if it can work while the vehicle is moving and the speed is over a practical level (more than 30 km/h), necessary, in order to cover large distances.

When it comes to the sensors involved in the monitoring process, a wide range of solutions are to be found. Some of them [5] use accelerometers deployed on vehicles in order to measure not only the road surface influence on the vehicle, but also the amount of stress people inside the car feel from driving over a rough surface. Other solutions [8] are based on smartphone accelerometers, GPS and wireless connections in order to find a more user friendly approach.

In [9], video images processing is used in order to identify the potholes. This is considered to be a low cost solution, but there are some drawbacks regarding the needed computing power and available storage size.

A somehow different approach is described in [10] where a combined solution using laser technology and video cameras to detect road defects offers good results at a manageable hardware price.

An accurate rut depth measuring system is discussed in [11] using laser technology resulting in an accurate measurement system.

Two implemented solutions for high level road quality assessment are the Canadian road monitoring system ARAN [12] and the ROMDAS [13] system from New Zeeland. Both use a combination of laser, ultrasonic and video sensors to recreate the road profile within very thin margins of error. Another similar tool which is now also used in our country is presented in [14].

ROMDAS uses a Transverse Profile Logger based on an Ultrasonic Measurement System Array for high performance measurements.

All these solutions offer different degrees of practicality and different levels of precision more or less compatible with the standards in use. The main argument against the more exact laser based measuring systems is the high sensor acquisition price and maintenance costs. This would limit the number of vehicles to an unfeasible number compared to the length of the road network in need of monitoring.

Accelerometer based systems are less precise, but their running costs makes them available on a larger scale and therefore usable in a larger, more complex monitoring system [15].

3. System architecture

Our solution is based on using 3D accelerometer data in order to assess the magnitude of the asphalt degradation. It consists of 3 modules as follows:

- Road defect identification module
- Video capture module
- Central processing and data aggregation module

These modules are connected by wired and wireless connections. The road defect identification module and the video capture module are both deployed on the surveillance vehicle. The importance of having an on board processing system is analyzed in terms of wireless sensor networks characteristics.

The advantage of local data processing is emphasized by the small quantity of data which has to be stored over the period of time between two consecutive data retrievals. This means our system has no need for a large storage unit and we don’t need to send large quantities of data over long distances, reducing communication related costs and power consumption.

This method gives us the opportunity to implement a system based only on Wi-Fi communication technology which is, overall, cheaper than any other method. This is implemented by storing the computed data locally until a Wi-Fi connection is available.

The drawbacks of implementing a mobile processing unit include a higher power consumption (needed in order to process the data). This can be reduced by implementing algorithms which are not processor intensive, keeping our need for computation power as low as possible.

The components of the mobile platform are depicted in Fig. 1.

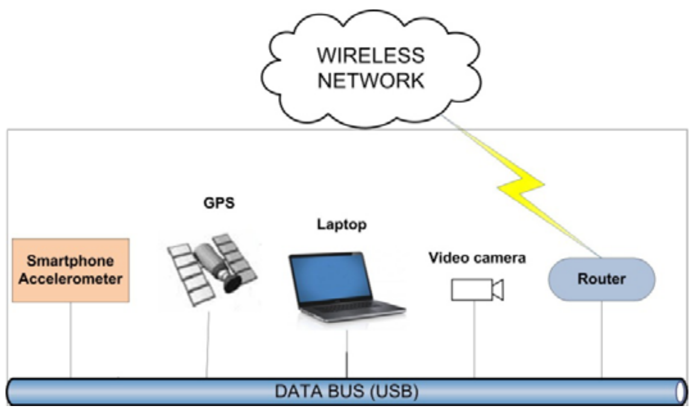

Fig. 1 Mobile platform components.

The connection between several patrolling platforms and the global processing unit is made using wireless communication (Fig. 2). This allows us to continuously (if a wireless connection is available) or periodically feed data into the system.

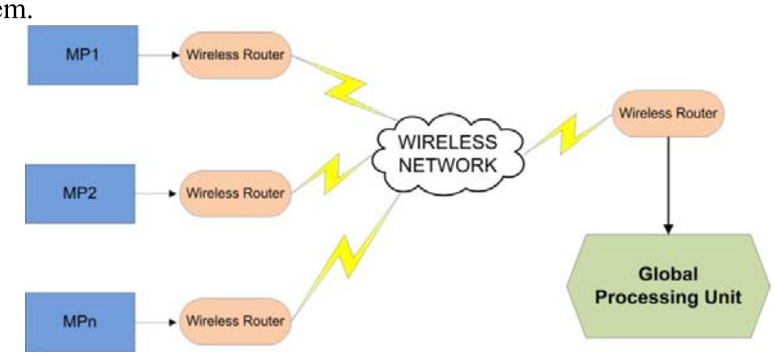

Fig. 2 Mobile platform connections to the Global Processing Unit.

By patrolling the urban road network with a fleet of vehicles equipped with monitoring platforms, most of the defects can be identified and then shown to our clients (drivers, authorities) using a GIS platform. The database keeps a complete historical evolution of parameters over geographical areas, feeding data to sophisticated statistic tools which are then able to post process the information making useful predictions.

4. Implementation and test results

For our experiments we used an iPad monitoring application deployed on a vehicle capable of recording 3D accelerations at a 20 Hz frequency rate, GPS coordinates and speed. The primary objective is to find a road defects identification method that can run on a mobile device (laptop, tablet, smartphone). The second objective is to find a way to discern between fine grained road pavement and more rugged pavements which might affect the driving style and wheel adherence especially under severe weather conditions. All the tests have been conducted using the same car and the iPad has been deployed in the same position, parallel to the car floor.

As an enhancement, we will try to find a way to measure defects using only accelerometer and GPS provided data.

A. Mobile platform data interpretation algorithms

Several approaches have been tested in order to find the most suitable way for data interpretation. We started by taking a look to our rough data (Fig. 3) and decided that the most important axis for our experiments is the Z axis, perpendicular on the Earth gravitational field vector. Therefore, we concentrated our efforts on identifying the most suitable filtering method in order to detect road defects.

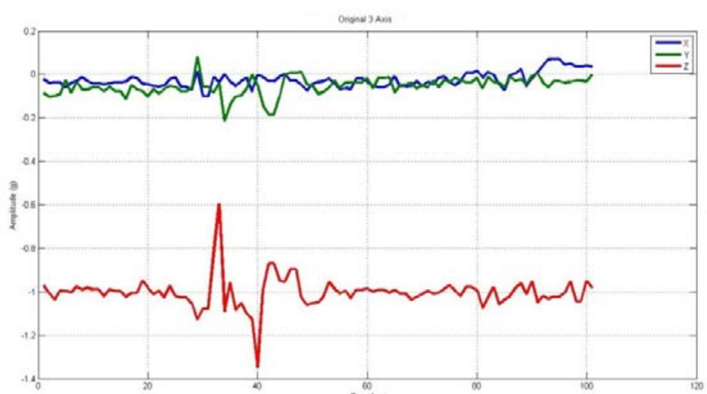

Fig. 3 Rough data from the iPad 3D accelerometer (with one speed bump).

The first achieved goal has been to distinguish between fine and rough grained roads. This was possible by using a standard deviation over a sliding window (Fig. 4) algorithm calculated by (1).

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2} \quad (1)$$

Considering

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (2)$$

Where

- s is the standard deviation;
- n is the interval width;
- x_i is the samples acceleration and $\overline{x}$ is the mean acceleration.

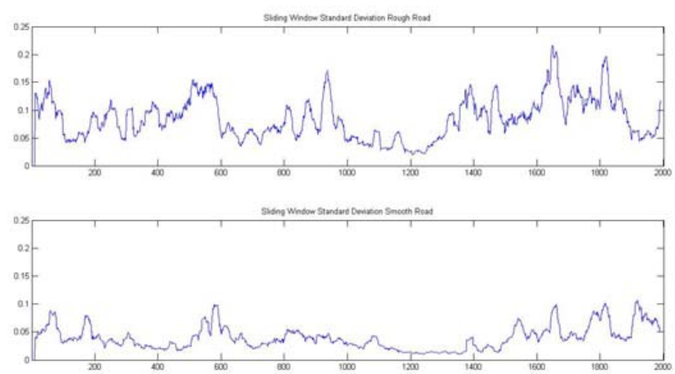

Fig. 4 Standard deviation (Z axis) over a sliding window (Smooth and Rough Road Segments).

Calculating the standard deviation over a sliding window, we can assess the quality of the road over a given road segment. Here, in the first picture, we have encountered an older pavement segment, characterized by a rough surface. In the second graphic, standard deviation over a smooth road section is depicted.
Another parameter that gives as a good measurement of the road condition is the moving average. The same portion of road described above has been depicted as moving average in Fig. 5.

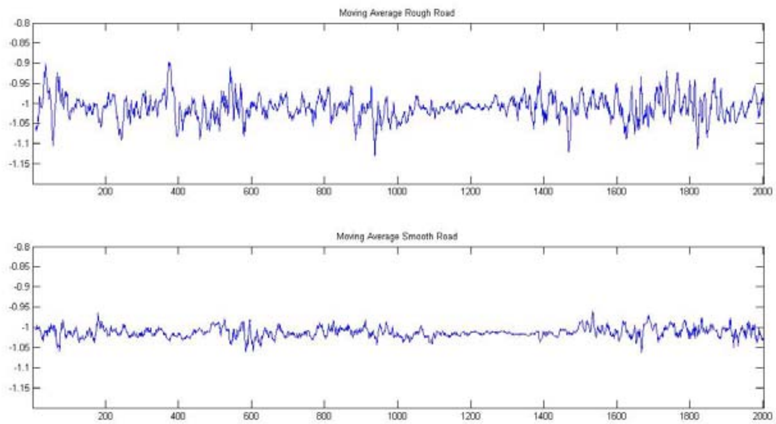

Fig. 5 Moving average values over two road segments with different granularity.

On the other hand, we wanted to identify road defects such as potholes, road bumpers, railway crossings, etc. The first possible approach is to consider a given threshold as a defect marker and every measurement above it is considered to be a road anomaly (Fig. 6).

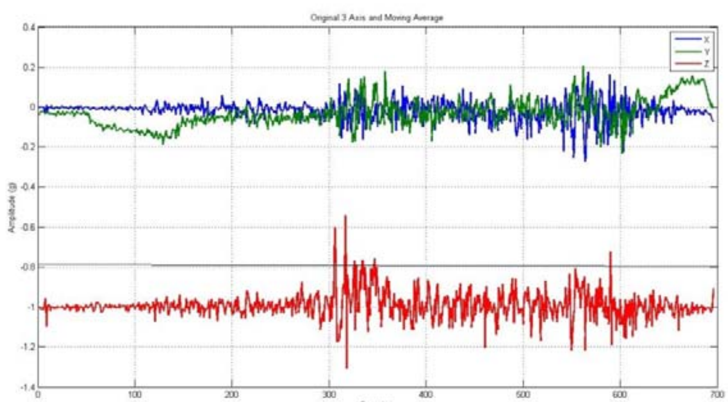

Fig. 6 All values of the Z axis over the -0.8 g are considered road defects.

Another method is to use a filter in order to mitigate the effect of the noise aver the entire data. From the unfiltered data, there is a great risk of identifying false positives and even to lose track of some defects.

After experimenting with several filters: Moving Average, Moving Weighted Window, Gaussian, Median, FIR and Low Pass Butterworth from

Matlab, we obtained the best results using a more complex filter [16] (described below).

If we consider y to be the noisy rough signal and x the signal to be estimated, we define the function to be minimized as (3):

$$\mu\|x-y\|^2+\|Dx\|_1, \tag{3}$$

Where D is the finite differences operator.

The results of applying this filter to the Z axis accelerometer signal are depicted in Fig. 7.

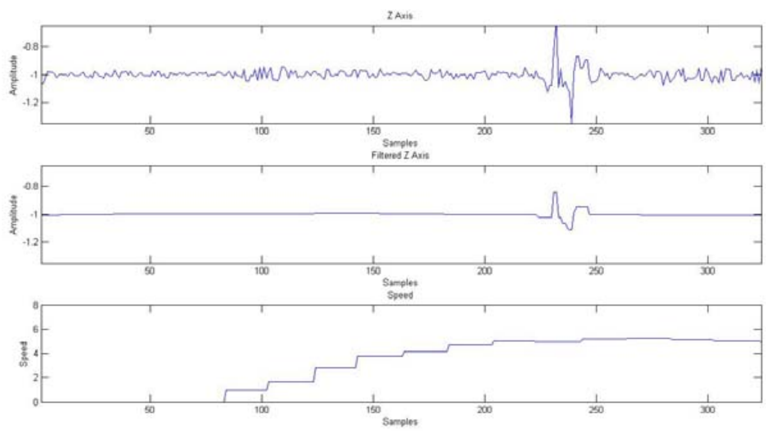

Fig. 7 Filtered signal for Z axis.

By filtering data, more accurate estimations and less false positives are reported. Another filter we used is a low pass filter that enables us to better estimate the shape of the signal (Fig. 8).

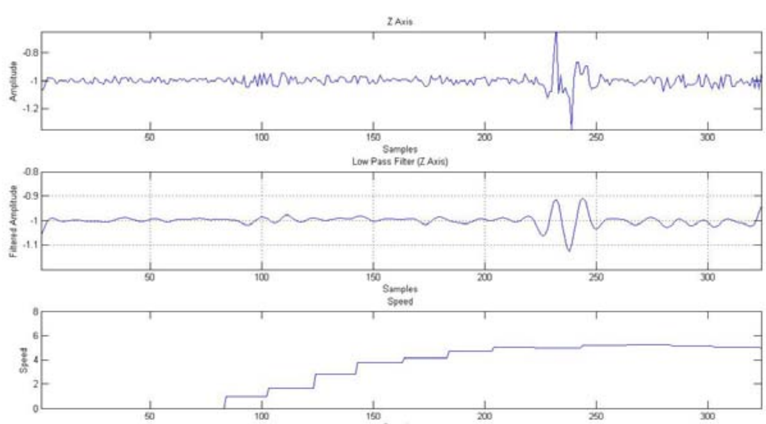

Fig. 8 Low pass filter output helps us to better understand the signal shape.

As we can prove from Fig. 9, the filtered signal gives a much better estimation of the signal shape than the moving average. Therefore it is much easier to use it in order to find the defects and determine their characteristics and dimensions.

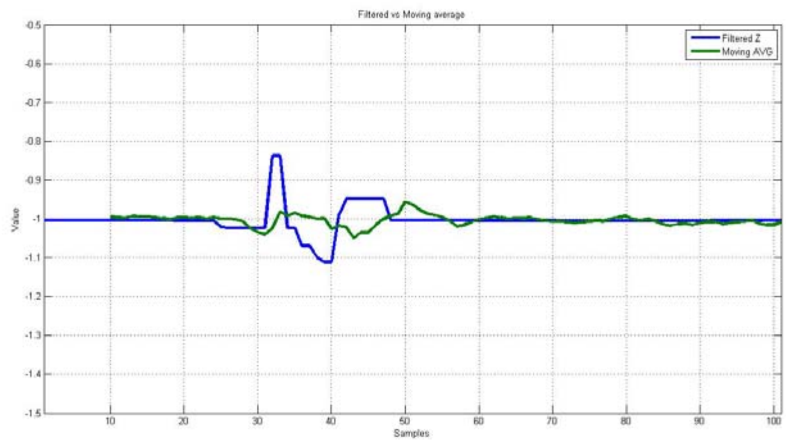

Fig. 9 Filtered Signal vs. Moving average for a road bump region.

The conclusion is that the most useful approach is to filter the accelerometer signal and set a threshold on the filtered signal in order to find the road defects.

Further processing enables us to put road defects into different categories based on their impact upon passing traffic. Therefore, if a road defect creates high magnitude oscillation, the auto vehicle structure can be damaged.

Another way of categorizing road potholes is due to their length. Because we always have the vehicle speed from the GPS, and we know the sampling rate, we can assess the pothole dimension on the axis which is passes by the vehicle.

For the bumper above, we have an estimated speed of about 4.5 m/s and the number of affected samples for a set of wheels is 2. Therefore, the estimated bump transversal length is calculated using the formula:

$$L = v \times \frac{s}{f} \tag{4}$$

Where

- L is the transversal length of the road defect;
- v is the last recorded speed of the vehicle;
- s is the number of affected samples;
- f is the sampling rate.

Which, in this case, results in L=0.45 (meters) which is a good estimation for the speed bump in Fig. 10.

Fig. 10 Identified speed bump.

Therefore, by only employing tools which are now available on smartphones and simple mathematical algorithms, we can now have a better look for example, at the amount of materials needed for repairing a pothole.

B. Global processing unit data aggregation

Having in mind the fact that our collected data is of a dynamic nature, we need to permanently reassess the defects state in regard to the last information we receive.

The defect clustering algorithm needs to assess the location of every recorded defect and correlate it to all the data gathered from the same spot. Unfortunately, taking into account the smartphone GPS accuracy, it proves to be a bit of a challenge as a singular defect might be recorded in two different locations close to each other (usually less than 10 meters). This does not affect data consistency if there is only one defect in the region. Based on the Haversine formula (5), we can measure the distance between the recorded locations and decide if it belongs to the same recorded defect.

$$Dist = 2RSin^{-1}\sqrt{Sin^2\left(\frac{[\phi_B - \phi_A]}{2}\right) + Cos\phi_A Cos\phi_B Sin^2\left(\frac{[\lambda_B - \lambda_A]}{2}\right)} \qquad (5)$$

Where:

- R is the Earth radius R = 6378.137 km;

- λ_A, λ_B : Latitudes of the given points;
- ϕ_A, ϕ_B : Longitudes of the given points;
- *Dist* is the distance between the two points.

Sometimes, many road defects are close to each other and the distance between them is well below the GPS error margins. If the acceleration signature is clearly different from one defect to another, we might draw the conclusion that this area is affected by more than one road defect.

In fact, what is useful for the drivers and even for the municipality is the general conclusion that the area is marked as a damaged road.

A large area covered with lots of recorded defects might be subject to a visual inspection. Our system is also capable of recording images of the road segment where abnormal accelerometer values are recorded.

A statistical determination of the most probable location of the defect when several candidate positions are available is possible by calculating the centroid (Fig. 11) of all the recorded values inside a given radius. The centroid position is therefore recalculated after each new received location. If more than one cluster of points can be discerned from the recorded locations, several centroids are calculated based on the confidence radius and the point cloud density.

The centroid coordinates are calculated using the following formula (6):

$$X_C = \frac{1}{n}\sum_{i=1}^{n} X_i \qquad , \qquad Y_C = \frac{1}{n}\sum_{i=1}^{n} Y_i \tag{6}$$

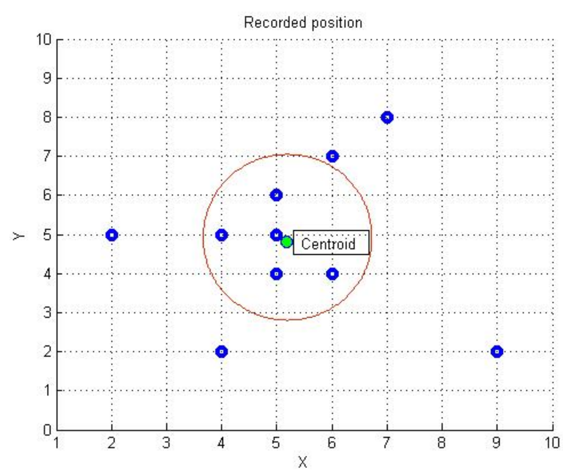

Fig. 11 Most probable pothole position from a cloud of recorded candidates.

Based on this algorithm, we studied the values gathered from a circuit which has been measured three times. Because of the differences in speed and traffic conditions and the lack of extensive data, we cannot obtain a great accuracy. The results are shown in Fig. 12.

Fig. 12 Average positions of the encountered defects along a 1.2 km track.

Our measurements also included some false negatives that were not consistent with the visual inspection of the road. These have been taken into consideration only if they were recorded in at least 2 of the 3 measurements. This approach is consistent with the visual inspection of the test circuit, helping us eliminate some of the false positives.

A statistical view of the inspected data is shown in Table 1.

Table 1

Identified and interpreted road defects

Circuit	Identified Defects	False Positives	False Negatives	Real defects
1	15	2	0	13
2	12	1	2	13
3	14	3	2	13
Interpreted	13	0	0	13

Displaying the average positions of the recorded defects, we offer valuable information to drivers and authorities which may take corrective measures in order to restore road quality.

5. Conclusions

The proposed road surface monitoring solution consists of several mobile platforms equipped with accelerometer sensors, GPS, small data storage and processing capabilities and wireless communication. By processing the gathered information locally first, the need for larger local storage facilities is addressed.

The economical advantage is obtained by employing only commercially available low cost sensors mounted over an already existing public transportation network or other volunteering vehicles. Being based on a modular architecture, the system can easily be fixed or upgraded. By using only Wi-Fi communication, other more expensive communication services are avoided. In our research, overall system robustness has been achieved by employing several monitoring units, in order to obtain a high level of redundancy. The rather noisy gathered data can be sent to central processing unit where, by employing specific data aggregation techniques, the algorithms can determine the location, size and associated risk of every road defect.

Our tests have shown that the proposed system can assess the road pavement characteristics within tolerable error margins.

Using a GIS platform, the usability of the entire system is greatly enhanced. The collected data can be further integrated with other related databases in order to create more complex applications (for example, integrating the processed data into a navigation system might help develop an early warning system for drivers).

For the future, our goal is to increase the accuracy of the detection algorithm, so that it can better differentiate between several classes of defects, based only on their 3D acceleration signature. A self calibration algorithm may hold the answer to different vehicles accelerometer deployment which, at this point causes data interpretation problems due to their different structural characteristics.

Acknowledgement

This work was supported by doctoral program *POSDRU/107/1.5/S/76813.*

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