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A mobile application for road surface quality control: UNIquALroad

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Abstract

The monitoring of road surface conditions plays a key role in ensuring safety and comfort to the various road users, from pedestrians to drivers. Furthermore, having information on infrastructure quality allows road managers to guarantee an adequate maintenance. These data can be given and used at the same time by users, by means of mobile devices, widespread in Italy and in the World.

The main aim of this paper is to realize a simple application, which can be installed on several devices (smartphone/tablet), that allows to use sensors piggybacked on them in order to monitor road surface quality. Experimental tests are carried out on urban roads of Calabria (Italy) to validate and test the mobile application. In particular, the accelerometer is used for detecting surface conditions, in terms of potholes and bumps. The Global Positioning System (GPS) is employed to know in real time the location of vehicles and of road surface anomalies. Five different devices were used, all placed in a test vehicle in three different placement conditions. For the validation process, only one device was used, completely bound in an utilitarian car. The algorithm developed to detect road bumps and potholes is based on the analysis of the acceleration signal in terms of high-energy events; three filters are applied on the original signal. Moreover, verification of the rate of false detections and undetected road anomalies is planned, using georeferenced photos that allow the correct localization on the map and the assessment of the correspondence between the elements, detected with the accelerometer, and real road conditions.

The results obtained show that our application could be used as an useful automated sensing system for road quality.

Keywords: Accelerometer; GPS; Bump detection; Road anomalies.

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1. Introduction

Road surface anomalies, such as potholes, speed bumps, railroad crossing, joints, can determine some problems for vehicles and can affect road users safety. Road quality assessment plays a key role in infrastructure management and it is useful to an adequate allocation of road maintenance operations. At the same time, informing drivers on road real conditions, in terms of the presence of bumps, potholes, or other anomalies, has a great importance in order to make the transportation system more safe, efficient and comfortable [1], [2].

As is well know, road energy efficiency, in terms of fuel and vehicle's parts consumption and of CO_2 emissions, is affected by road evenness [3], [4], [5]. Fuel consumption is primarily due to acceleration necessary to regain speed after deceleration determined by bump events. Moreover, braking and bumps and/or potholes crossing generate vehicle's parts consumption as concerns brakes and suspensions.

For these reasons in the last few years mobile sensor computing systems have been developed to collect data on road quality with the final aim of giving real-time information to road users. The monitoring of road conditions can be done by means of several sensors piggybacked on mobile devices. Most of these smartphones/tablets uses a three axis accelerometer to collect acceleration data due to vehicles motion on road anomalies and a GPS receiver to obtain location information of the road segment in question. In this way each event can be located and it is possible to create a database of road anomalies by means of a central server to which data collected by users can be reported and registered [6].

In the light of the abovementioned facts, authors developed a road detection system based on the use of Android mobile devices, driving a test vehicle and an utilitarian car for the validation process.

Mobile devices used in the experimental tests are all equipped with a GPS receiver and an accelerometer with a 3 dimensional Cartesian frame. To evaluate our approach a set of field tests, type of mobile devices and accelerometer placements was chosen, as described in Section 4. A study on accelerometer vertical orientation was also carried out (see Section 3).

In particular, this paper investigates on three main issues: 1) the possibility of visualizing on a map the correct localization of road anomalies detected in the experimental tests; 2) the analysis of the different high-energy acceleration signatures registered (in particular referred to the vertical acceleration a_z) by means of a post processing algorithm trough which the signal was filtered (see Section 5); many high energy event, in fact, should not be associated with road anomalies; 3) the evaluation of the relationship between road anomalies dimensions, such as speed bumps length or height, and the peak values of the acceleration signal.

An hand-labeled detection of the field test anomalies was also done to verify how the automatic system is able to reproduce the real surface condition. This detection consisted in a bumps and potholes manual count and classification, according to their dimensions; georeferenced photos allowed the assessment of the correspondence between the elements, detected with the accelerometer, and road real conditions.

Section 2 reports some related works about road anomalies detection; experimental results are shown and discussed in Section 6.

Finally, conclusions are drawn in Section 7.

2. Literature review

In literature there have been several works on road surface quality monitoring with mobile devices.

Microsoft [2] made a work for monitoring road and traffic conditions through the Nericell system. A mobile smartphone and its sensors, such as the accelerometer, the GSM radio, the microphone and the GPS receiver were used. Three types of devices were used: a smartphone, a phone and an external accelerometer. The accelerometer used for the monitoring of road conditions and for bumps and potholes detection was represented by a 3D Cartesian frame which was oriented as the car Cartesian frame. For the well-orientation, Euler angles were used, with the sequence ZYZ. Two speed conditions (low and high) were considered for detecting bumps;

for each condition a particular algorithm was used. At least, another important objective of the Nericell project was the evaluation of the system energy-efficiency. The GSM and the GPS were used for the correct localization of road anomalies, the first one always running, the second only if it was necessary.

The University of Latvia carried out two studies in 2011 considering smartphones with Android OS. In the first work [7] two auto, three mobile devices and their sensors were used. In particular, the accelerometer was used for the potholes detection, while a GPS receiver allowed the correct localization of the detected road anomalies. The bump event could be established with four different algorithms. Furthermore, data obtained from the different devices were compared.

In the second study [8], one auto and four devices were used. The same algorithms of the previous work [7] were employed for bumps detection.

In Yu-chin Tai et al. [1], the acceleration data, collected by means of a mobile device while riding a motorcycle on about 60 Km of roads, were analyzed with the aim of detecting road surface anomalies. Several sensors were used to collect localization and acceleration data: the HTC Diamond platform with a built-in accelerometer, an external GPS sensor, the NCS Navi R150 + GPS logger and a voice recorder. Two riding speeds (30, 40 Km/h) were selected for the experimental tests. The study approach was founded on three main hypothesis: 1) vibration patterns similar for a given stretch of road; 2) test vehicle suspension system in good conditions; 3) the 3D Cartesian frame of the accelerometer fixed with the frame of the vehicle. Filtering operations on the acceleration signal allowed to have useful and trustworthy values from the original data. Results showed that the method achieved a precision of 78.5% in detecting road anomalies correctly.

The study conducted by Eriksson et al. [9] investigated on a system of road surface monitoring named Pothole Patrol (P2) deployed on 7 taxis running for thousands of kilometers in Boston city. Accelerometer data were measured to detect potholes and other road anomalies. The architecture of P2 road monitoring foresaw a set of equipped vehicles with several sensors (3 axis accelerometer, a GPS receiver) and a central server where clustering filters were applied to remove spurious detections. The server created a database combining the data collected from the equipped vehicles with the aim of producing a set of road anomalies. Three different placements of the accelerometer were chosen in order to evaluate how the placement can affect data quality.

The potholes detection algorithm was founded on the use of different filters on processed data. The system accuracy was also investigated. Results showed that P2 detection flagged less than 0.2% of samples from good roads as potholes.

3. Accelerometer orientation: Euler Angles

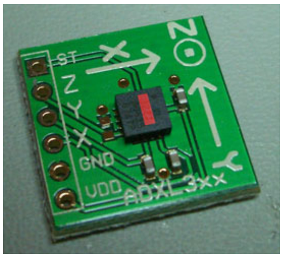
The accelerometer is a sensor that can detect linear accelerations along one, two or three axes, by measuring the inertial forces. A three-axis accelerometer, which can be represented with an 3 dimensional Cartesian frame fixed x'y'z', is piggybacked on mobile devices [10] (Figure 1).

Considering this frame, the accelerometer detects the following accelerations: a_x' , a_y' e a_z'. In order to determine the accelerations undergone by the vehicle when there are road surface anomalies, the accelerometer must detect what happens in the direction perpendicular to the vehicle.

According to the SAE [11], the x axis identifies the longitudinal direction, the y axis the transverse one and the z axis the perpendicular direction to the xy plane.

To detect road anomalies the z axis direction must correspond with the z' axis direction. If this condition occurs, the accelerometer is well oriented, otherwise it is not well oriented and it must be reoriented.

The reorientation can be achieved through the Euler Angles, three independent parameters which allow to define the orientation in space of any body through a succession of elementary rotations [12, 13]. In this work, the XYZ sequence was used: a rotation around the x axis by an angle α (roll angle), one around the y axis by β (pitch angle) and one around the z axis by γ (yaw angle).



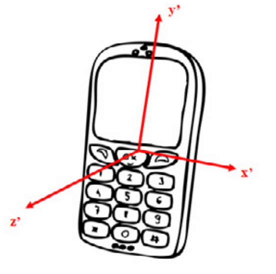


Fig. 1. (a) 3D Cartesian frame with respect to the accelerometer; (b) 3D Cartesian frame with respect to the accelerometer piggybacked on Android mobile/ devices

When the vehicle is in a stationary condition the only acceleration registered is along the z axis and it is equal to the acceleration of gravity:

$$a_x = 0\,m/s^2;\quad a_y = 0\,m/s^2;\quad a_z = 9.81\,m/s^2 = 1g \tag{1}$$

Starting from this condition it is possible to evaluate two of the three Euler angles :

$$\alpha = tan^{-1}\left(a_y'/a_z'\right) \qquad \beta = tan^{-1}\left(-a_x'/\left(\sqrt{(a_y')^2+(a_z')^2}\right)\right) \tag{2}$$

The yaw angle (γ), useful to reorient the x' and y' axes respect x and y axes, can be calculated in a dynamic condition, but it is not estimated in this research. The reoriented accelerations along the three axes can be estimated by means of the equations (3, 4, 5), where c and s represent the cosine and the sine of the angles, respectively. Furthermore the roll angle α is defined in the range [-π; π], while the pitch angle β in [-π/2; π/2] [10].

$$a_{xreor} = c_\beta a_x' + s_\beta s_\alpha a_y' + c_\alpha s_\beta a_z'; \tag{3}$$

$$a_{yreor} = c_\alpha a_y' - s_\alpha a_z'; \tag{4}$$

$$a_{zreor} = -s_\beta a_x' + c_\beta s_\alpha a_y' + c_\beta c_\alpha a_z' \tag{5}$$

4. Experimental plan

In order to investigate on the feasibility of the UNIquALroad application, the experimental plan shown in Figure 2 was designed and performed.

As it is possible to see, thirty measurements (round trip of about 4 km) for each test site were carried out; overall about 120 km of road were travelled. Five measurements for each direction and each device placement condition were done with the aim of having statistically valid data. The driving speed ranged from a minimum of 25Km/h to a maximum of 40 Km/h; two different accelerometer frequencies were set.

Three different accelerometer placements inside the vehicle were chosen in order to investigate how the mobile device orientation can affect the quality of the signal. These three conditions were classified as follows: 1) completely fixed bound condition; 2) partial bound condition (axes x and y fixed to the vehicle frame, whereas each phone could move along the vertical direction); 3) free condition (each phone could move inside the vehicle without constrains). A wooden support for the mobile devices, placed in the boot of the test car, was used for the devices placement in the first two cases of orientation (each device was bounded with angle bars). The completely fixed bound condition was realized by means of some pieces of velcro, which prevented the movement in the z direction. For the validation process, only one smartphone was used, completely bound in an utilitarian car. Overall about 8 Km were travelled; the speed ranged from a minimum of 30 Km/h to a maximum of 50 Km/h because the road is located in the urbanarea of Cosenza (Italy).

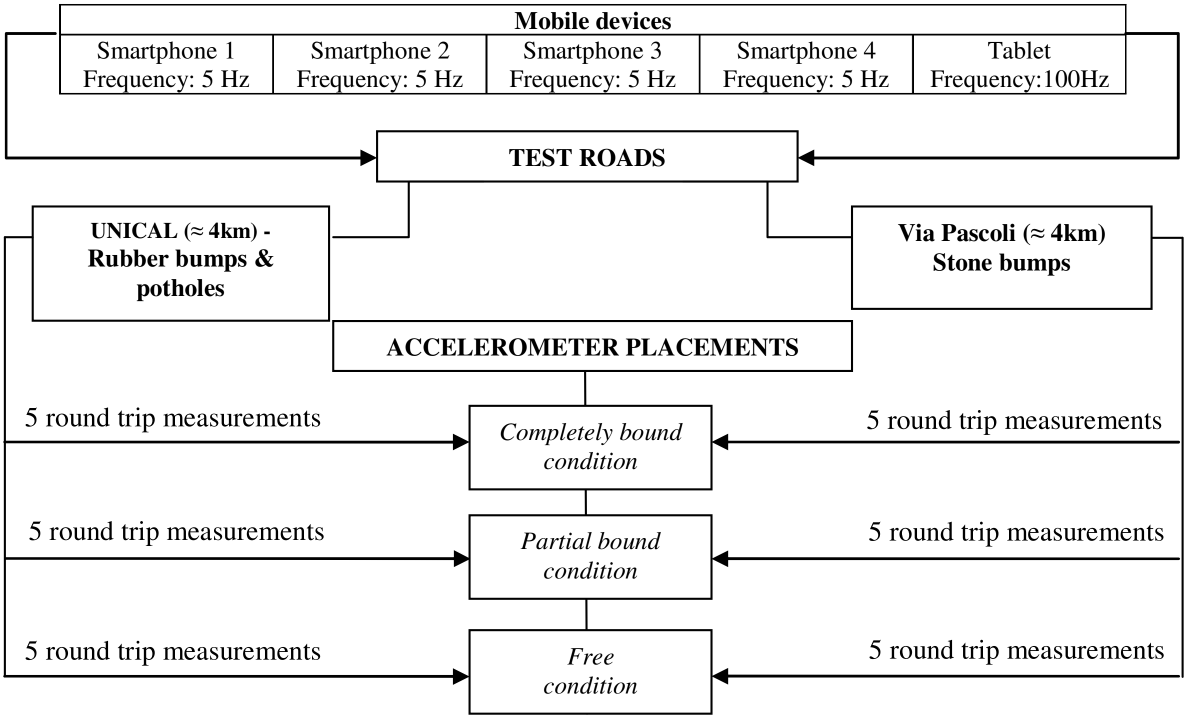


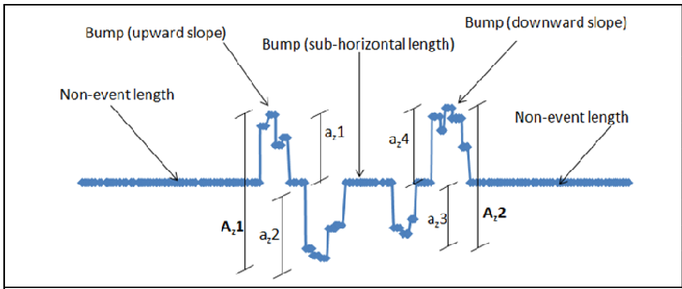
Fig. 2. Experimental plan

5. Signal analysis and bump detection post-processing algorithm

The algorithm developed to detect road bumps and potholes is based on the analysis of the acceleration signal in terms of high-energy events. The aim was the unambiguous identification of these events and the possibility of associating the acceleration impulses registered with a specific road anomaly. Some processing filters were applied on the a_z acceleration (reoriented) because of the need to "clean" the signal and to reject one or more non-anomaly event.

In order to better understand how the type and dimension of bumps can affect the acceleration signal in terms of energy peak acceleration values, one event was studied for both stone and rubber bumps, as shown in Figure 3 and Figure 4. For Via Pascoli test site (an extra-urban road) the vehicle speed ranged from a minimum of 25 Km/h to a maximum of 40 Km/h, whereas for Unical test site the speed was limited under 30 Km/h because this road is located in the Arcavacata University Campus.

The acceleration signal reproduces the stress for vehicle suspensions; in the case of stone bumps the signal has a first peak-valley drop that corresponds to the upward slope of the bump, whereas the second valley-peak event is due to the downward slope and the effects on the suspensions that are extended beyond the end of the bump. The rubber bumps are characterized by a unique peak-valley drop due to the fact that they have a shorter length. It is also possible to see a difference in terms of high energy peaks, probably due to the difference in bump height.



	V [Km/h]					
	≤ 30		30/40		≥ 40	
	M*	S*	M*	S*	M*	S*
a_z1 [m/s^2]	14.5	0.6	16.0	0.6	17.5	0.7
a_z2 [m/s^2]	6.0	0.8	6.0	0.8	5.0	0.7
a_z3 [m/s^2]	6.5	0.3	6.5	0.7	3.0	0.4
a_z4 [m/s^2]	16.0	0.8	17.5	0.6	19.5	0.6
A_z1 [m/s^2]	8.5	0.5	10.0	1.1	12.5	0.4
A_z2 [m/s^2]	9.5	1.2	11.0	1.9	16.5	0.3

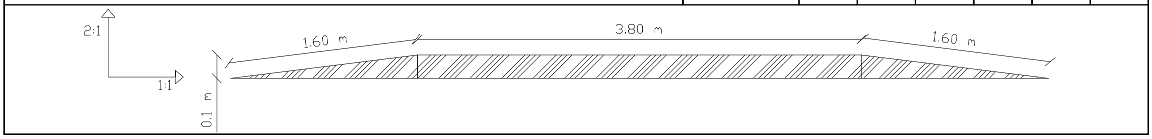
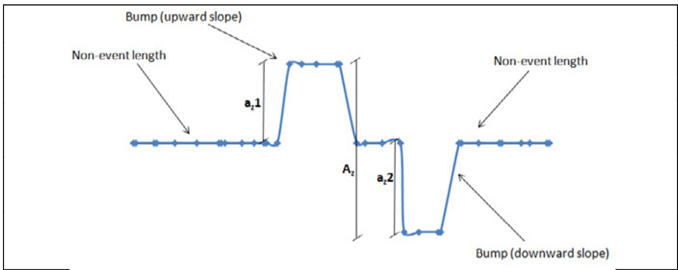


Fig. 3. High-energy event analysis: peak values for a stone bump (Legend: M*: average value; S*: standard deviation)



	V [Km/h]	
	25 ≤ V≤ 30	
	M*	S*
a_z1 [m/s^2]	13.5	0.97
a_z2 [m/s^2]	7.0	1.1
A_z [m/s^2]	6.3	0.7

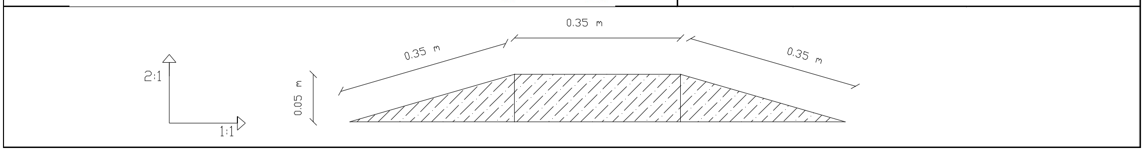


Fig. 4. High-energy event analysis: peak values for a rubber bump (Legend: M*: average value; S*: standard deviation)

In the light of the above mentioned analysis, three main filters were used as described below:

- LFF (Low Frequency Filter): this filter permits to remove low frequency components due to the background noise.

$$a_z = \begin{cases} \overline{a_{z0}} & if\,(a_{z0\,min} \le a_z \le a_{z0\,max}) \\ a_z & if\,(a_z \le a_{z0\,min};\ a_z \ge a_{z0\,max}) \end{cases} \quad (6)$$

where a_z is the reoriented acceleration, $\overline{a_{z0}}$ is the mean acceleration value for a signal associated to a stationary condition of the same test vehicle, $a_{z0\,min}$ and $a_{z0\,max}$ are the minimum and the maximum acceleraion values for the stazionary condition, respectively.

- SF (Speed Filter): each acceleration peak associated with a stationary condition of the vehicle (speed=0) is rejected. These peaks can be due to the closing of car's door or boot.

$$a_z = \overline{a_{z0}} \quad if\,(a_z \leq a_{z0\,min};\; a_z \geq a_{z0\,max}) \quad and \quad v = 0 \tag{7}$$

where v is the vehicle speed.

- SPF (Small Peaks Filter): this filter rejects the events for which the peak registered in the signal is lower than a specified threshold, established by means of a statistical analysis for all registered data. These peaks could be due a too high speed that can amplify small road anomalies not considered in this work.

$$a_z = \overline{a_{z0}} \quad if\,(a_{zt\,min} \leq a_z \leq a_{zt\,max}) \tag{8}$$

$a_{zt\,min}$ and $a_{zt\,max}$ are the minimum and the maximum acceleration values associated to small peak events, respectively. These two thresholds are calculated as the mean values on all registered data.

An example of the algorithm application on the registered signal is shown in Figure 5.

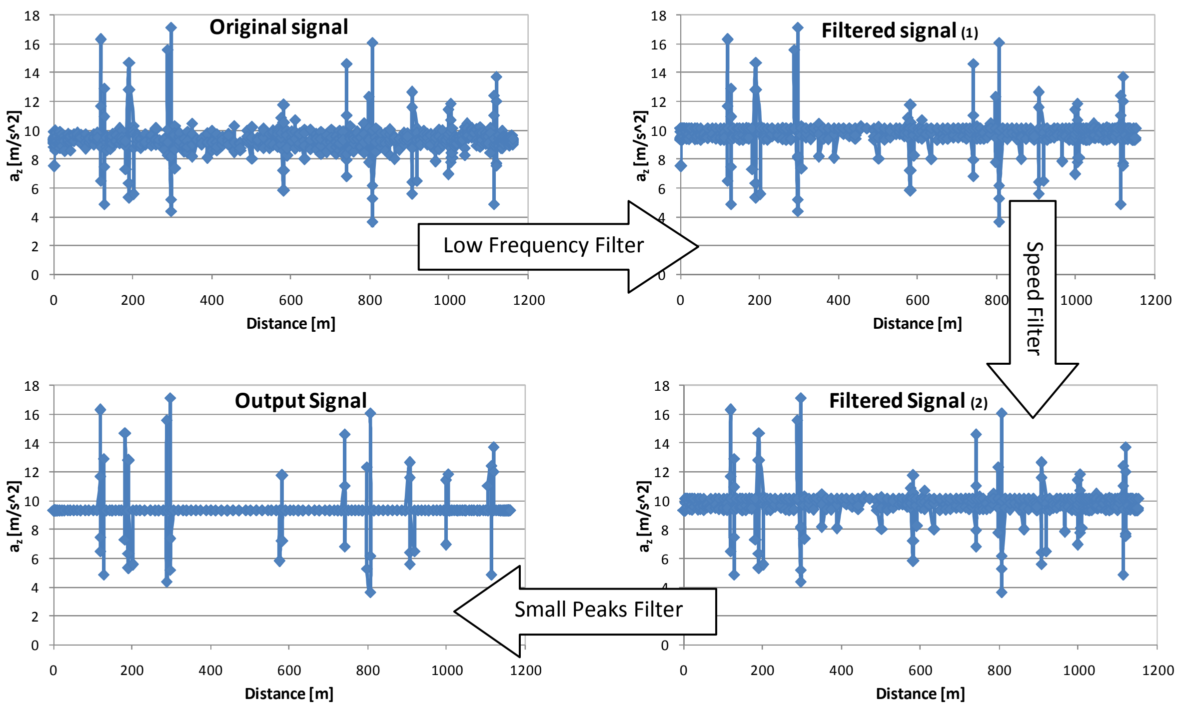


Fig. 5. Algorithm application on the registered signal

6. Results and discussion

One of the main issues of this research was the correct identification of the high-energy events in the acceleration signal related to road anomalies. In the light of the abovementioned fact, the first data analysis consisted in the comparison between the output acceleration signal for the three conditions of the devices placement. For each case the peak associated to the bump detection is correctly identified, although the free placement has an amplification effect on the peak event.

All recorded data (for each test site and each device) confirm that the reorientation of the vertical acceleration permits to reach a correct localization of road anomalies, regardless the device placement in the vehicle.

The localization of the road test anomalies, handily detected by means of georeferenced photos, was compared with the event identification with the accelerometer for both the test sites. The graph in Figure 6 (relative to Via Pascoli test site) shows that for this test site in which the only anomalies consist in stone bumps of high dimensions the post processing algorithm of the signal was adequate to single out 98% of bump events.

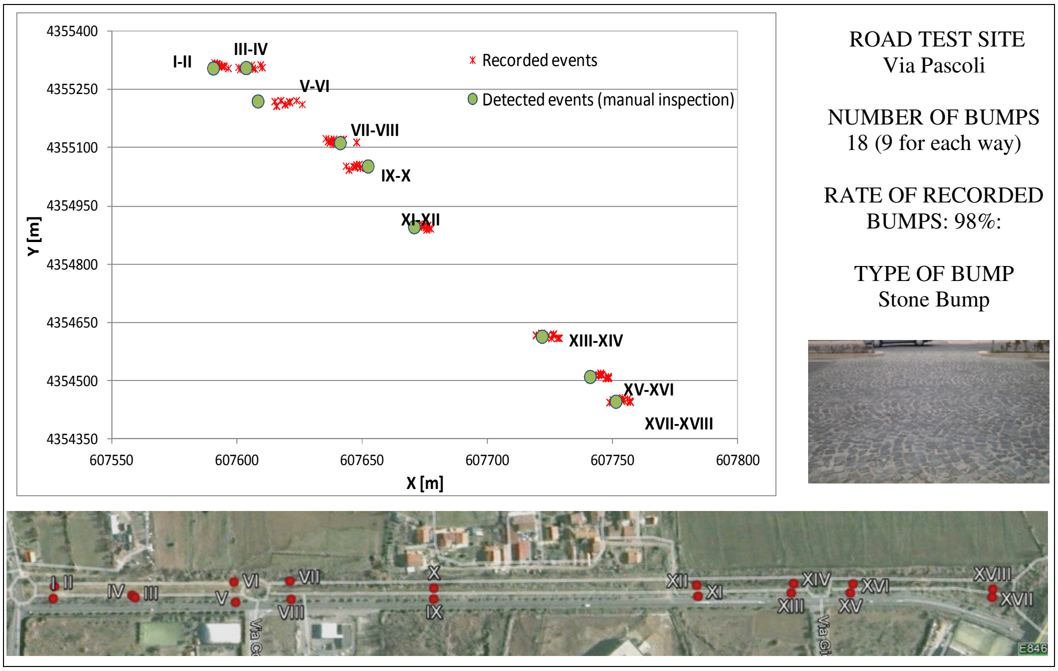


Fig. 6. Localization of road anomalies (Test site: Via Pascoli)

In the case of Unical road test site, characterized by several anomalies (rubber bumps, rough pavement surface, potholes of different dimensions), it was found that the filters used in the signal analysis allow to detect 90% of bump events whereas the localization of potholes is not always correct. The rate of potholes false positive events was about 35%.

In all five devices, UNIquALroad records more events than the real anomalies, detected by means of manual inspection, probably because the road pavement surface of this test site is characterized by many irregularities in the longitudinal profile that influence the vehicle motion and the effect on the user's perception of ride quality. However, the rate of bumps false positive events was zero in both test sites. UNIquALroad was also applied on another set of data collected on Viale Mancini test site (Cosenza, Italy) by means of one smartphone at a frequency of 5Hz. This test site is characterized only by bump anomalies. In this way it was possible to better estimate the system accuracy and the proposed method performance.

Experimental results are shown in Figure 7. As it is possible to see, the filters allow to identify road anomalies with a rate of recorded bumps of around 93%; the application did not record only one of the 13 bumps detected with the manual inspection.

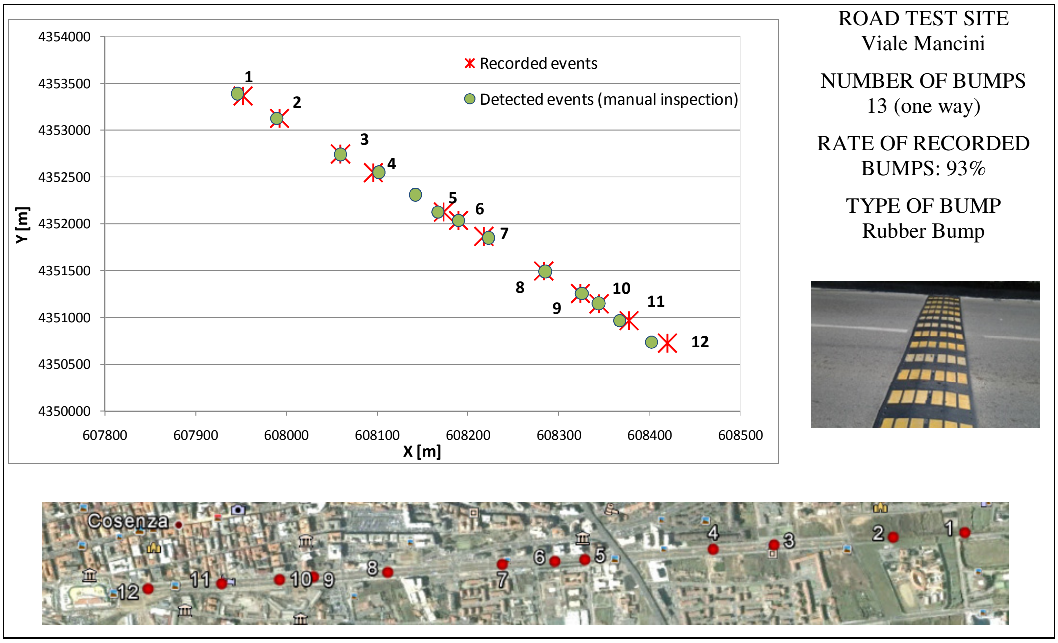


Fig. 7. Localization of road anomalies (Test site: Viale Mancini)

Conclusions

This paper investigates on the feasibility of the UNIquALroad application for road surface quality control in terms of speed bumps and potholes detection by means of sensor equipped mobile devices. Five different devices (four smartphones and one tablet) were used, all placed in a test vehicle in three different conditions (completely fixed bound, partial bound and free).

The algorithm developed to detect road bumps and potholes was based on the analysis of the acceleration signal in terms of high-energy events; three filters were applied on the original signal. A reorientation of the vertical acceleration a_z', achieved through the Euler Angles, was also carried out. The study of the energy peak values of the acceleration signal showed some differences between the two types of bumps analyzed: in the case of stone bumps the signal has a first peak-valley drop followed by a valley-peak event associated to the length of the element and to the effects on the vehicle suspensions extended beyond the end of the bump. The rubber bumps, shorter than the stone ones, are characterized by a unique peak-valley drop. The comparison between the original acceleration signal for the three conditions of the devices placement showed that the free placement of the device has an amplification effect on the peak event.

The post processing algorithm was adequate to single out 98% of bump events for Via Pascoli test site. In the case of Unical road test, the rate of recorded bumps was about 90%, whereas the rate of recorded potholes was around 65%. The rate of bumps false positive events was zero in both test sites.A validation study of the proposed method was carried out on another set of data collected on Viale Mancini test site. Results showed that also in this case the rate of rate of recorded bumps was around 93%.

It is noted that this project was run under the auspices of the research project "M2M – Mobile to Mobility: Information and communication technology systems for road traffic safety". The main objective of this project is giving real-time information on road quality to road users trough mobile sensor computing systems in order to reduce risks and to make the transportation system more safe and comfortable.

Outcomes of this study are expected to benefit both practitioners and researchers, although some aspects of the work need to be improved, especially referring to a more accurately pothole detections to reduce the rate of false positive events.

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