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DESIGN OF A LOW-COST DETECTING AND LOCATING SYSTEM FOR PAVEMENT DISTRESSES BASED ON VIBRATION ACCELERATION SIGNAL

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Abstract. *Rapid and accurate collection of road surface distresses data on broad urban road network is crucial for routine maintenance and rehabilitation. In this paper a low-cost yet high efficient system for road surface distresses detection and localization is presented. The proposed system is based on collecting Global Positioning System (GPS) and accelerometer data and can be installed to an ordinary vehicle. Such system has data logging and visualization functions for replaying and analyzing the changes of the same road segment. The design of the hardware and the operating software for the developed system is described in detail. Also the system is tested and verified in site and the results are presented.*
Keywords: Pavement distress, Tri-axis accelerometer sensor, Lab VIEW, GPS, Video clips

1. **Introduction.** The pavement monitoring and evaluation are essential requirements for effective road traffic control and management. Rapid and accurate collection of road surface distresses data on broad urban road network is crucial for routine maintenance and rehabilitation. However, the traditional method for pavement inspection relies on human observation, thus is quite costly, time-consuming, labor-intensive, and subjective [1].

To increase the efficiency and reliability, an inspection method utilizing digital video and image analyses to record and identify the pavement surface roughness was proposed [2,3]. While the image based approach may encounter technical difficulties in processing the acquired images, whose quality are influenced by several factors [4]. Moreover, some systems only can conduct real-time recording (on film or tape) and perform off-line processing.

In analogy to the video record which "looks" at the surface of the pavement, the vibration-based (build-in) system "feels" the ground situation based on mechanical responses of the testing vehicle [5]. This has motivated researchers to use different sensors to structure their systems. Note that most strategies proposed therein are accelerometer sensor based, such as the "Pothole Patrol (P2)" [6], the "Vehicle Intelligent Monitoring System (VIMS)" [7], the "Road Condition Monitoring with Three-axis Accelerometer and GPS Sensor (RCM-TAGPS)" [8]. In [9,10] accelerometer and GPS data are collected from mobile phones of large number of individual, anonymous car drivers. Similarly, fiber optic sensors are used in [11], which also showed good responsibility to the impact and had a nice damping shake. However, most exiting methods cannot literally reflect the evolvement of the pavement distresses, which limits the practical application of the methods.

The laser scan technique is another non-contact measuring method, using the laser rang finder with the help of acceleration sensor to gain the surface evenness [12]. However, the cleanliness of road surface, the speed and load of detecting vehicle all can influence the detecting results. Meanwhile, the price of the device is fairly high, and their capabilities in adverse weather condition remain to be improved.

Approaches using radar sensors have also been studied. One takes advantages of ground penetrating radar to scan the form and positing of pavements internal structure [13]. However, the acquired data can be analyzed under the understanding of as-built documents, field investigation and coring drilling results, which are hard to achieve and compare.

In this paper, we describe a low-cost system for pavement surface distresses based on vibration acceleration signal, capable of performing daily fast detecting and continuous monitoring of the pavement distresses, and furthermore, providing their evolvement trend, which is deemed favorable for efficient road maintenance scheduling. The proposed method takes advantages of both image-based and vibration-based methods. Since pavement roughness is the main external stimulation of the vehicle vibration, a carefully selected tri-axis acceleration transducer is used to capture these vibration signals. A Charge-Coupled Device (CCD) video camera takes video recorder all over the process, providing corresponding video clips when needed based on time matching. The GPS is used to obtain the time, vehicle speed and geographic position. Finally, the pavement distresses spots will be labeled on the electronic map. The operating software is designed based on virtual instrument programming language Laboratory Virtue Instrument Engineering Workbench (Lab VIEW), dealing with the analysis of amplitude-frequency characteristic, pavement feature extraction and distress determination.

The rest of this paper is organized as follows. In Section 2, we discuss the background and motivation of the proposed system. In Section 3 and Section 4, we present the detection system with the detailed description about the data acquisition system and the software design. The experimental results are reported in Section 5, followed by the concluding remarks and further works in Section 6.

2. **Background and Motivation.**

The pavement distress is the main external source of shock and vibration to moving vehicle. The impact vibration is discrete with a relatively short time and high vibration intensity. In this section, the response of vertical vibration of a quarter-vehicle model (see Figure 1 [14]) is simulated to illustrate the feasibility of the detection system.

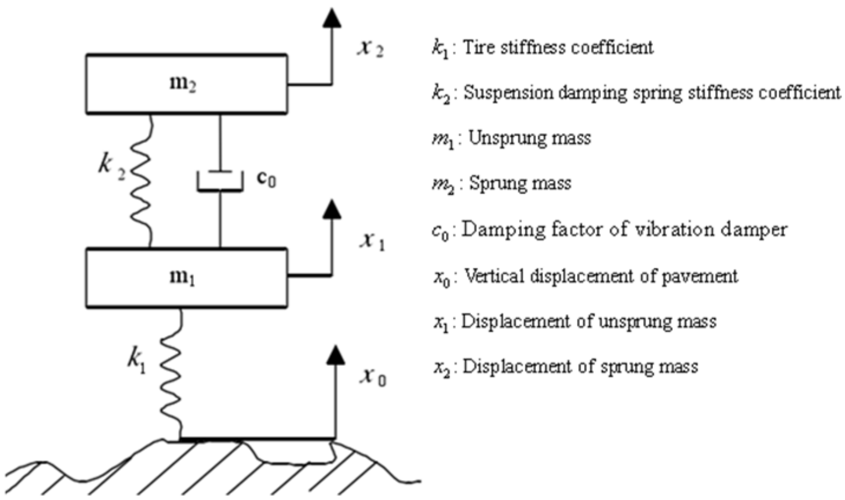

FIGURE 1. Quarter-vehicle passive suspension model

By Newton's second law and corresponding vibration theories, we establish the kinetic equations as follows

$$m_1\ddot{x}_1 - k_2(x_2 - x_1) - c_0(\dot{x}_2 - \dot{x}_1) + k_1(x_1 - x_0) = 0 \tag{1}$$

$$m_2\ddot{x}_2 + k_2(x_2 - x_1) + c_0(\dot{x}_2 - \dot{x}_1) = 0 \tag{2}$$

Define state variables

$$X_1 = x_2 - x_1,\ X_2 = \dot{x}_2,\ X_3 = x_1 - x_0,\ X_4 = \dot{x}_1,\ X = [X_1\ X_2\ X_3\ X_4]^T \tag{3}$$

which represent, respectively, the strain of wheels, the vertical velocity of the car body, the degree of the suspension dynamic disturbance and the velocity of unsprung mass. Define the output variables

$$Y_1 = x_2 - x_1,\ Y_2 = \dot{x}_2,\ Y_3 = k_1(x_1 - x_0),\ Y_4 = \dot{x}_1,\ Y = [Y_1\ Y_2\ Y_3\ Y_4]^T \tag{4}$$

Note that Y_2 so defined represents the vertical velocity of the car body, and the derivative of such variable is the acceleration signal that is of particular interest to the development of the detection system.

The state equation of the model can be described as

$$\begin{cases} \dot{X} = AX + Bu \\ Y = CX \end{cases}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & -1 \\ \frac{-k_2}{m_2} & \frac{c_0}{m_2} & 0 & \frac{c_0}{m_2} \\ 0 & 0 & 0 & 1 \\ \frac{k_2}{m_1} & \frac{c_0}{m_1} & \frac{-k_1}{m_1} & \frac{-c_0}{m_1} \end{bmatrix},\ B = \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \end{bmatrix},\ C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & k_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

Based on the above 1/4 passive suspension model, we develop a simulation package using MTATLAB/SIMULINK, with parameters taken from a JETTA GTX, $m_2 = 559.6$kg, $m_1 = 116.4$kg, $k_2 = 33000$N/m, $k_1 = 604990$N/m, $c_0 = 2200$Ns/m.

The corresponding responses of acceleration signal in time domain with different amplitudes of input are shown in Figure 2. It is observed that when there is an external exciting input, the acceleration signal first appears an acute change, then decays rapidly under the action of damping, and finally keeps low frequency oscillation. The amplitude of the output acceleration signal increases accordingly with the input, and vice versa.

In conclusion, vertical acceleration change of suspension system can well reflect the pavement distresses, which motivates the method of using acceleration for pavement distresses determination as described in what follows.

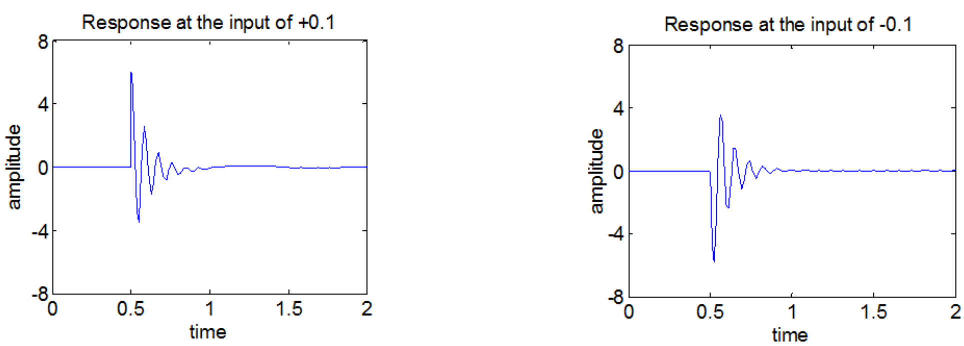

Figure 2. Responses of acceleration signal with different inputs

3. The Detection System. Motivated by the above simulation and observation, we propose to build a system for payment distresses detection and localization by utilizing the vibration acceleration signal. The overall structure of the system and the data acquisition unit are outlined.

System structure: The proposed detection system is shown in Figure 3, which mainly composed of tri-axis acceleration transducer, Data Acquisition card (DAQ card), computer, GPS receiver, video camera and electrical control gear.

Data acquisition unit: The data acquisition system is composed of vibration data acquisition module, GPS data receiving module, video camera module, data processing module and display module (see Figure 4). The LC160 tri-axis accelerometer and NI9233 DAQ card mainly contribute to the vibration data acquisition module. The HOLUX GR-89 GPS is used as the receiver module. A normal CCD video camera is used to take video recorder all over the process of detection. The data process and display module are both achieved by a common personal computer.

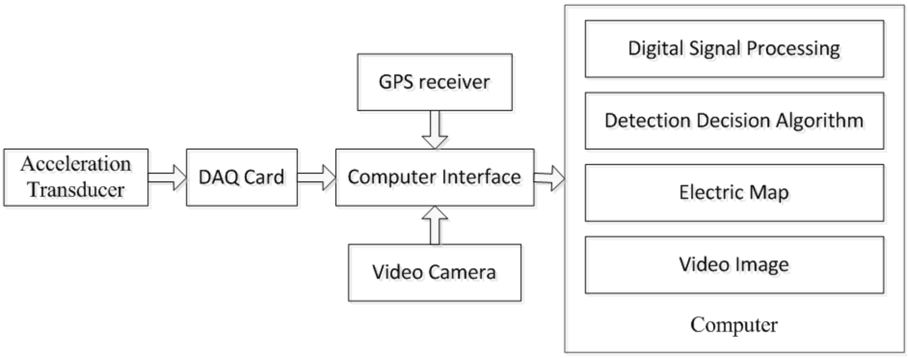

FIGURE 3. Overall structure of the pavement distress detection system

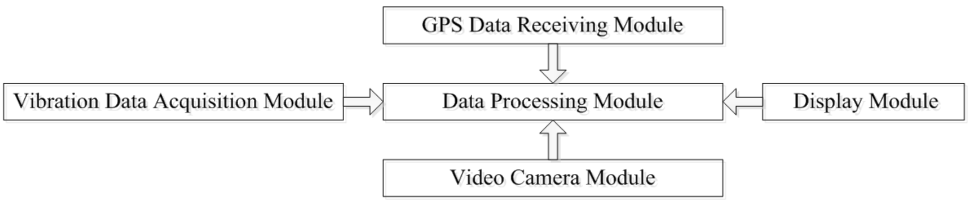

FIGURE 4. Data acquisition system

4. Software Design. The system software is mainly designed based on the Lab VIEW, responsible for the saving and analysis of acceleration signal, pavement feature extraction, and pavement detection decision [15-17]. We choose SQL Server Database for the storage of the information, while C# is in charge of the video association, image display and electronic map labeling.

Figure 5 shows the schematic diagram of the video clips extraction. Once a pavement distress was detected, the system will label its corresponding time such as t_2 automatically. Thus, if needed, one can obtain its video clip between $t_2 - \Delta t$ and $t_2 + \Delta t$. The value of Δt depends on the initialization setting.

There are five basic types of standard GPS data, including GPGGA, GPRMC, GPGSA, GPGSV and GPVTG. We use the second one GPRMC, which is considered to be the minimum GPS data format. One piece of its information is pointed out in Figure 6.

The distress detection algorithm is an important part of this system. However, note that we just use a simple threshold algorithm here, since this paper is not focused on developing the algorithm.

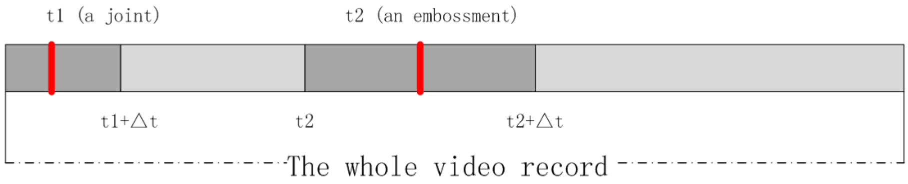

Figure 5. The schematic diagram of the video clips extraction

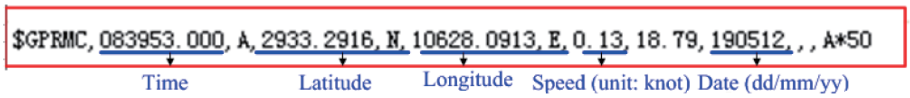

Figure 6. Corresponding meaning of the GPRMC

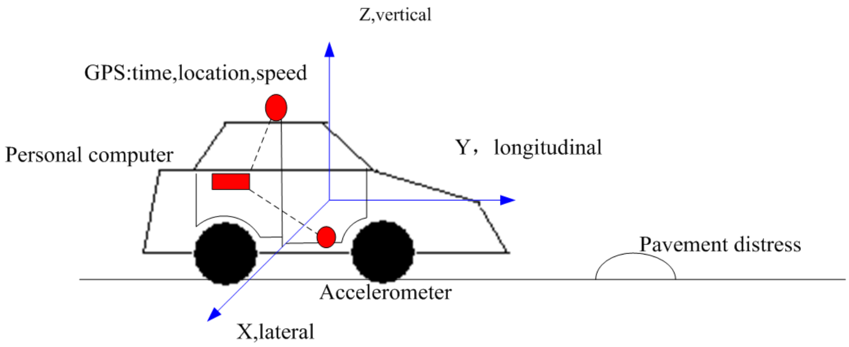

Figure 7. Abridged general view of the testing system

5. **Experimental Verification.** A physical test system has been built to verify our work, using a car from Dongfeng Citroen Inc. The abridged general view of the testing system is shown in Figure 7. We test this system in an experimental road keeping an even speed around 40km/h, collecting 913000 data points, with the sample rate of 2000 points per second, shown as set of three-axis acceleration signals in Figure 8, typical signals with their corresponding pavement distresses in Figure 9. Obviously, the system is feasible, when comparing with the simulation signal discussed in the previous section.

We have labeled some typical signals with their corresponding pavement distresses in Figure 9, and then enlarged a part of the z-axis signal which represents for a typical embossment (see Figure 10). Obviously, the proposed detection system is feasible, when comparing the characteristics of practical output signal with that of simulation signal discussed in the previous section.

The marked points as shown in Figure 11 are the distresses detected, which have been located on the electronic map. When clicking the marked point, it will display the corresponding prompts and video clips around that time. By repeating the detection process over the same road segment (i.e., three times within one month), we were able to visualize clearly the variation and evolvement of the distresses by examining the recorded video clips, which is fairly useful for late pavement management and scheduling.

6. **Conclusions.** This paper introduced a detecting and locating system for pavement distresses based on vibration acceleration signal, which, as compared with most existing systems (devices), exhibits at least two attractive features with regards to both hardware and software: 1) It contains comprehensive functions required by efficient road maintenance scheduling with a considerable low cost by using ordinary vehicle and computer which avoids the additional fee; 2) The developed system can be installed into an ordinary vehicle to capture large amount of distresses data, and one can group these individual data to visually and quantitatively evaluate road surface distresses and gain an insight

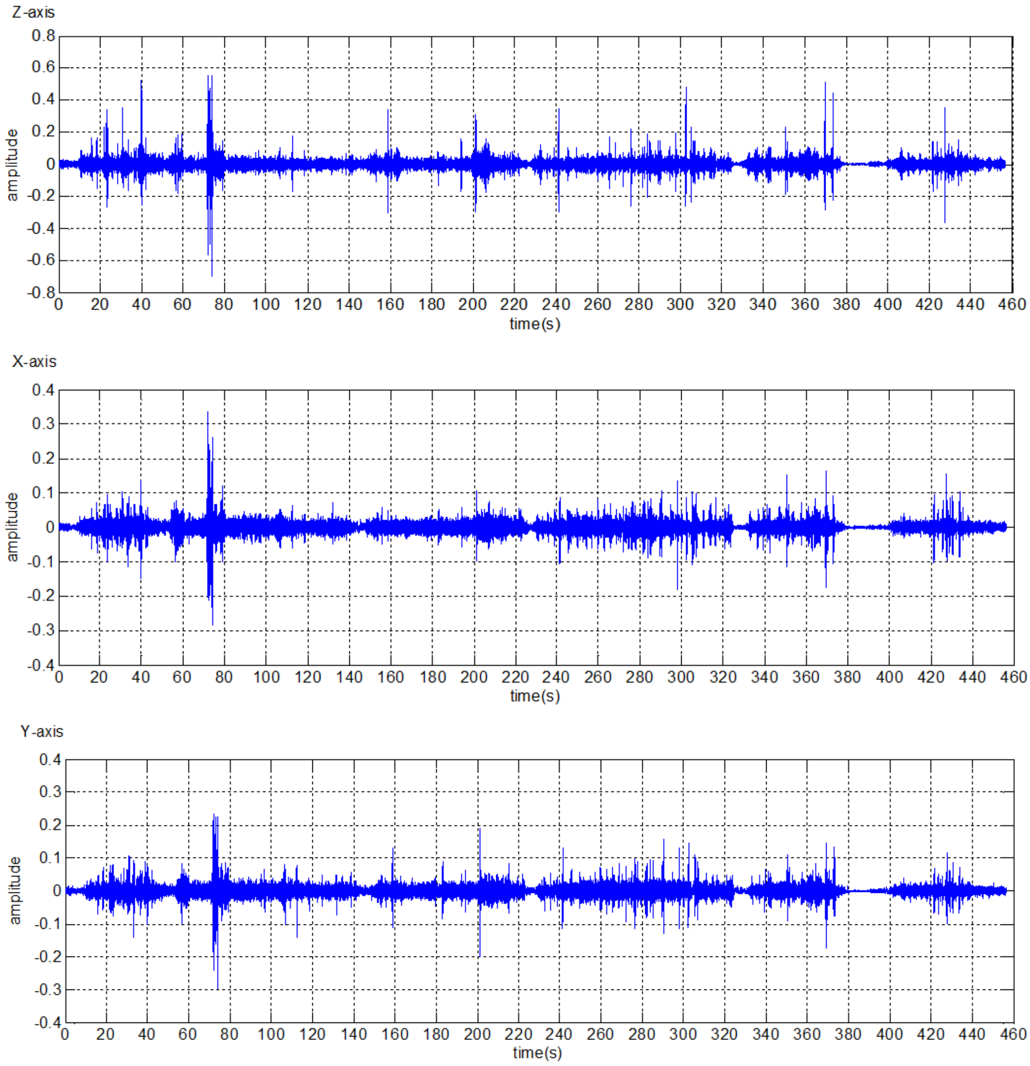

FIGURE 8. Three-axis acceleration data

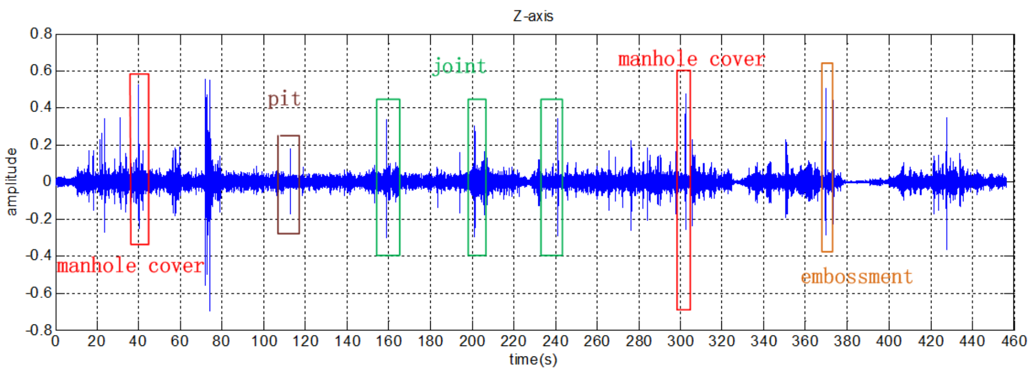

FIGURE 9. Typical pavement distresses signal

into the evolving trend of the distresses. Real-time experiment has verified and validated the benefits of the proposed system.

It should be pointed out that just like any other devices the developed system in the current version has its limitations. The future work should be focused on improving the accuracy and robustness of the system over varying vehicle wheel-road interaction conditions (such as different vehicle approaching angles, and different vehicle driving

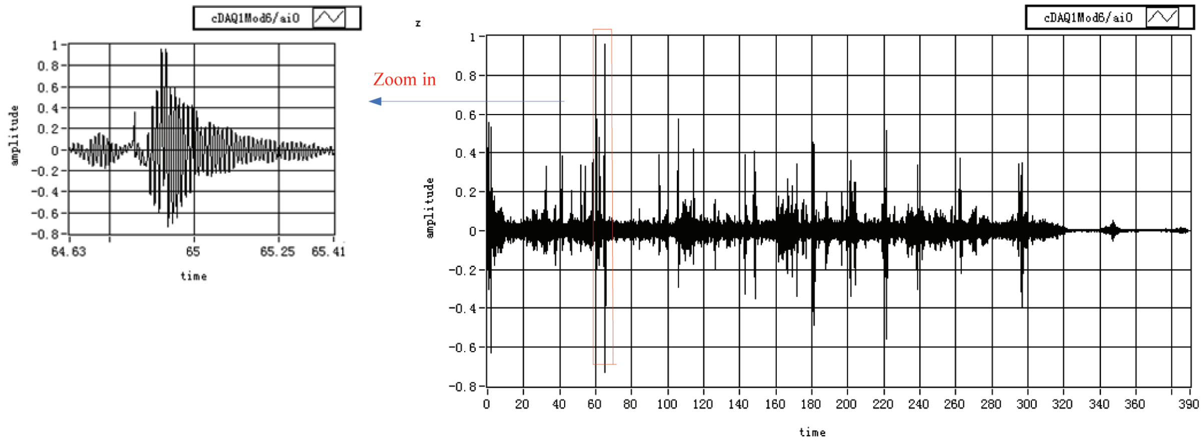

FIGURE 10. Z-axis signal and its partial enlarged view

FIGURE 11. Electronic map labeling

speeds). It is also worth investigating the performance of the system when the sensors are installed at different locations of the vehicle in data collection.

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