Road Condition Monitoring Using On-board Three-axis Accelerometer and GPS Sensor

Kongyang Chen[1], Mingming Lu[1,2], Xiaopeng Fan[1], Mingming Wei[1], and Jinwu Wu[3]
[1]Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences，Shenzhen, 518055, China
[2]Central South University, Changsha, 410083, China
[3]Shenzhen Transportation Depot Group, Shenzhen, 518040, China
Email :{ky.chen, lumm, xp.fan, mm.wei}@siat.ac.cn, wujw@sz95000.com

***Abstract*—A study by US Federal Highway Administration has shown that road condition is an essential factor of highway quality and smooth roads will lead to more comfortable driving experience and less municipal investment. International Roughness Index (IRI) has been widely used to measure pavement smoothness because it can provide a consistent rating for different measurement tools. However, existing measuring tools based on IRI are usually very expensive. In this paper, we present a low-cost vehicle-based solution, Road Condition Monitoring with Three-axis Accelerometers and GPS Sensors (RCM-TAGPS), by using a cheap three-axis accelerometer and a GPS sensor embedded in a vehicle to monitor the road condition. We analyze the Power Spectral Density (PSD) of pavement roughness, estimate IRI, and classify the pavement roughness level into four levels according to a Chinese industry standard. Experimental results show that RCM-TAGPS can evaluate pavement roughness level correctly, even under some interference like potholes, manholes and decelerating belts, and the total cost of RCM-TAGPS in each vehicle is no more than 50 dollars, which is about 1/4400 to 1/160 of the existing system used in civil engineering and municipal engineering.**

Keywords-Road condition monitoring; three-axis acclerate sensor; Power Spectral Density(PSD); International Roughness Index(IRI); pavement roughness level.

I. INTRODUCTION

Road condition monitoring [1-3] is a challenging problem in the field of road transportation infrastructure all over the world. A zone in bad condition may damage the vehicles on it, endanger the drivers, and even cause accidents. City municipalities have spent millions of dollars to maintain and repair these roadways. However, it is still a challenging problem to keep these roadways in good condition.

Expensive road monitoring system: City municipalities are much concerned with global roughness information of a certain road, because the whole road would be repaired if it is considered to be disqualified. In China, the road condition level is classified into four levels, according to *Technical Code of Maintenance for Urban Road CJJ36-2006*, which is one of the most important industry standards [20]. Current equipment used in measuring road condition is surveyed in [4], which is composed by accelerometers, distance measuring instruments, graphic displays or something other instrument. But these road condition systems are much too expensive, which cost 8,000 to 220,000 dollars. Therefore, these methods are too costly to be adopted in the whole urban district.

Different statistic metrics: Pavement roughness [5] is one of the most important performance metrics of road condition, and it can evaluate whether the driving is comfortable and safety or not. Power Spectral Density (PSD) is the frequency characteristic of pavement roughness in the vehicle industry and academia [6]. Moreover, International Roughness Index (IRI) is another important metric, which was firstly adopted by the World Bank in the 1980s, and then widely used for evaluating the pavement roughness [7-8]. Therefore, one of our objectives in this paper is to find out the relationship between PSD and IRI, in order to evaluate pavement roughness comprehensively.

This paper describes the design, implementation and experimental evaluation of a road condition monitoring system, namely Road Condition Monitoring with Three-axis Accelerometer and GPS Sensor (RCM-TAGPS). Each vehicle is embedded with a three-axis accelerometer and a GPS sensor when traveling around the road to be monitored. Each vehicle also collects the information of three-axis acceleration and velocity with a high frequency. We then estimate PSD and IRI of the pavement roughness, based on these data on accelerations and velocity. Finally, we classify the actual road condition into four different levels according to *Technical Code of Maintenance for Urban Road CJJ36-2006*; in order to provide useful suggestions for road maintenance.

In section II, we provide an overview of the system architecture of RCM-TAGPS. In section III, we describe the details of data collection by three-axis accelerometers and GPS sensors. In section IV, we discuss a novel pavement roughness level algorithm based on PSD and IRI. We present the evaluation of RCM-TAGPS in section V. Finally, we conclude this paper in section VI.

This work was partially supported by the National Natural Science Foundation of China under Grant No.60903222, the National S&T Major Project of China under Grant No.2009ZX03006-001-01, Guangdong S&T Major Project under Grant No.2009A080207002 and the National High Technology Research and Development Program of China (863 Program) under Grant No. 2011AA010500

978-1-4577-0101-6/11/$26.00 © 2011 IEEE

II. SYSTEM ARCHITECTURE

RCM-TAGPS consists of a set of sensor embedded vehicles for data collection and a central server for evaluating the pavement roughness levels, as illustrated in Figure 1.

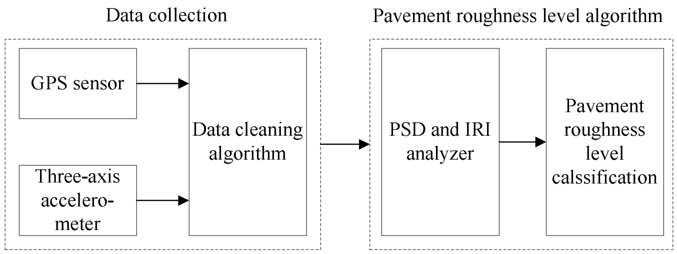


Figure 1. System architecture

Raw sensing data are collected by accelerometers and GPS devices. In RCM-TAGPS, we collect three direction accelerations from the accelerometer embedded in a traveling vehicle, and the current time, the velocity and the location from GPS sensors.

Due to the complicated environment and the precision of sensor devices, there are some noisy data. We apply the outlier removal method for data cleaning, and the interpolate points in curves where the data are missing. Each item in the set of the processed sensing data is a 4-tuple as follows:

< time, location, velocity, three-axis acceleration >

Sensor-equipped vehicles upload these processed data to the central server which maintains a database of all the detected data. The central server analyzes PSDs and IRIs of the pavement surface roughness, resulting in the comprehensive pavement roughness level according to the *Technical Code of Maintenance for Urban Road CJJ36-2006*, one of industry standard of the People's Republic of China [20].

III. DATA COLLECTION

RCM-TAGPS should provide continuous acceleration data from a three-axis accelerometer, and accurate time, location and velocity from a GPS sensor. In this section, we will describe our system design and data cleaning algorithm.

A. System hardware design

In RCM-TAGPS, the data collection module is composed of a three-axis accelerometer [9], a GPS sensor and a client microprocessor. Our system hardware design is shown in Figure 2.

The high performance MEMS motion module, LIS33DE, is adopted as the three-axis accelerometer. It is with ±2g dynamically measurement scale and 10000g high shock survivability. This module is with IIC/SPI digital output interface, 400kHz read/write clock frequency and 100Hz sampling frequency, so that it can be easily integrated into various kinds of host devices. Additionally, the power consumption of this sensor is less than 1mW, which results in power budget saving for the whole mobile embedded system.

Our GPS receiver is the vehicle-mounted HM-CZ02 GPS sensor. The communication baud of this GPS module is 2400 bits per second, while the GPS data is updated once per second. RCM-TAGPS reads accurate time, location and velocity if we follow the GPRMC format [10].

The client microprocessor is a 32 bits high performance Cortex ARM chip STM32F103. It is with a high clock frequency up to 72MHz, which is sufficient for our system. It can generate electronic signals to control time sequence of RCM-TAGPS, read the three-axis accelerometer and GPS sensor, and send data to the central server after processed. Simultaneously, we enable the build-in hardware watchdog, monitoring the real-time statues of software operations to ensure high reliability of the whole system.

Figure 2. System hardware design

B. Data cleaning algorithm

As we mentioned above, RCM-TAGPS reads 100 samples from the traveling vehicle’s three directions accelerations and one sample of GPS data (including time, location and velocity) per second, which is called raw sensing data.

During our experiments, we identify several technical challenges. Firstly, it is possible to miss some GPS data because the GPS sensor may not work properly in urban canyons among tall buildings and tunnels [11]. Secondly, the GPS receiver may not work well and provide valid GPS data for about several seconds at the beginning of the starting. Thirdly, a transmission error may occur when transmitting a large amount of data composed of accelerations and GPS data. Finally, the collected data from sensors are not normalized and the units used in GPS do not follow international unit.

To deal with these problems, we design the following data cleaning algorithm. We firstly delete the “bad zone” without GPS data, including the first several seconds after a GPS sensor powers on. Then, we remove the data when there is a transmission error or a miss of GPS data, and record the index at the missing points. After the removal of outlier data, we insert some interpolated points in curves where there is an outage. Our proposed algorithm generates these interpolation points at an interval of 10ms to keep the continuity of all the collected data. Finally, we normalize these sensor data to the international system of units. Specifically, we normalize the three- axis accelerations to the range from -2g to 2g, where g equals to 9.8 m/s^2, and change the unit of the velocity from sea mile per hour to kilometer per hour by using the conversion factor 1.852.

Our data cleaning algorithm results in the following sampling information: <time, location, velocity, three-axis acceleration>. The continuous three-axis acceleration is shown in Figure 3, where the curves are X-axis acceleration, Y-axis acceleration and Z-axis acceleration against sampling points from the top to the bottom in the Figure.

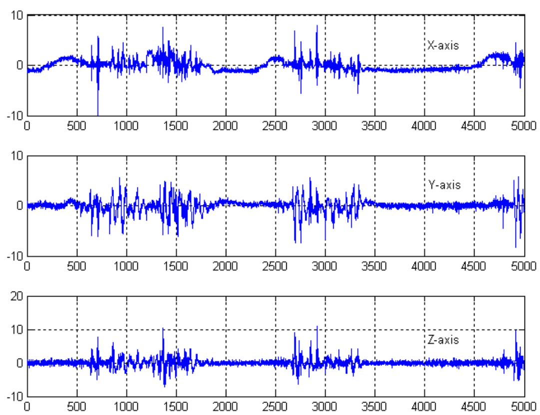


Figure 3. The continuous three-axis accelerations

IV. PAVEMENT ROUGHNESS LEVEL ALGORITHM

In this section, we present our pavement roughness level algorithm. The definition and solution of Power Spectral Density (PSD) are described in Part A. Then we introduce the International Roughness Index (IRI) and describe how to calculated IRI by PSD in Part B. According to the Chinese industry standard, the classification for pavement roughness levels is presented as a function of IRI in Part C. Finally, we propose the details of the pavement roughness level algorithm in Part D.

A. Power Spectral Density (PSD)

Power Spectral Density (PSD) is one of the most important metrics of pavement roughness, which is wildly used in the vehicle industry and academia. Compared with other metrics, PSD demonstrates the frequency characteristic of pavement roughness, reflects the amplitude of roughness, and also shows the excitation energy under frequency variation [12-13].

Experimental results show that pavement roughness can be modeled as a Gaussian distribution with zero mean and isotropic random character around the vibration source in the spatial domain. Based on the stochastic process theory, pavement roughness can be described as a normal stationary random process in the time domain.

According to the Wiener-Khintchine theorem [14-16], the following equations are composed of a couple of Fourier transform:

$$\begin{cases} S(\omega) = \dfrac{1}{2\pi}\displaystyle\int_{-\infty}^{\infty} R(\tau)e^{-j\omega\tau}d\tau \\ R(\tau) = \displaystyle\int_{-\infty}^{\infty} S(\omega)e^{j\omega\tau}d\omega \end{cases} \tag{1}$$

where τ represents the time interval, ω represents the angular frequency, $S(\omega)$ is the PSD roughness metric, and $R(\tau)$ is temporal auto-correlation function. $R(\tau)$ can be calculated by the following equation:

$$R(\tau) = E[x(t)x(t+\tau)] \tag{2}$$

where $E[\bullet]$ represents the expectation of the random process that can be estimated from the following equation:

$$E[x(t)] = \lim_{t\to\infty}\frac{1}{\tau}\int_0^{\tau} x(t)dt \tag{3}$$

As demonstrated by Eq. 1, $S(\omega)$ is the bilateral Power Spectral Density (BPSD). However, only the single Power Spectral Density (SPSD) is used in the engineering projects. Therefore, we change the spectral density from the negative frequency to the positive frequency as follows

$$S^{'}(\omega) = \begin{cases} 2S(\omega) & f \ge 0 \\ 0 & f < 0 \end{cases} \tag{4}$$

where $S^{'}(\omega)$ is the SPSD of pavement roughness.

Specially, if $\tau = 0$, we can deduce Eq.5 from Eqs.1~4 as follows:

$$R(0) = E[x^2(t)] = \int_{-\infty}^{\infty} S(\omega)d\omega = \int_0^{\infty} S^{'}(\omega)d\omega \tag{5}$$

B. International Roughness Inedex (IRI)

International Roughness Index (IRI), adopted by the World Bank in the 1980s, is the most widely used metric that is used to evaluate pavement roughness in highway transportation agencies. IRI is defined as the responses of the quarter car model [17-18] at a speed of 80km/h, where the vehicle parameters are recommended by the highway safety research institute (HDRI).

However, it is still difficult to realize the definition and the quarter car model. As discussed above, PSD can easily be estimated by the Fourier transformation of the temporal auto-correlation function. Hence, we aim to find out the relationship between IRI and PSD, so that we can obtain IRI easier. Here, the roughness standard deviation is considered as the intermediate variable.

Firstly, we analyze the relationship of PSD and the roughness standard deviation. Based on the probability and statistics theories, the relationship between the standard deviation and the expectation can be described as follows:

$$\sigma^2 = E^2\left[x(t)\right] + E\left[x^2(t)\right] \tag{6}$$

As the vehicle vibration can be modeled as a Gaussian distribution with zero mean and isotropic random character [12], we can infer that the expectation is approximate to zero. Hence, the standard deviation can be simplified as follows:

$$\sigma^2 = E\left[x^2(t)\right] \tag{7}$$

Combined with Eq.5, the relationship between the standard deviation and SPSD are described as follows:

$$\sigma = \sqrt{\int_0^{\infty} S^{'}(\omega)d\omega} \tag{8}$$

Secondly, we analyze the relationship between IRI and roughness standard deviation.

As we know, contrast experiments on pavements at Beijing, Changchun, and Nanjing have been carried out by the Ministry of Communications Highway Scientific Research Institute since 1990s [19]. The regression analysis results show that the relationship between IRI and the roughness standard deviation can be approximated by the following regression equation:

$$IRI = \frac{\sigma - 0.013}{0.5926} \tag{9}$$

C. Pavement roughness level classification

The pavement roughness levels can be classified according to the *Technical Code of Maintenance for Urban Road CJJ36-2006* [20], which is one of the industry standards in the People's Republic of China.

This industry standard shows that pavement roughness level is evaluated by Riding Quality Index (RQI), which is a comprehensive metric of driving comfort. The relationship between RQI and IRI is described as follows:

$$\mathrm{RQI} = 4.98\text{-}0.34 \times \mathrm{IRI} \tag{10}$$

The range of the value of RQIs varies from 0 to 5 normally. We set RQI to 0 if the value calculated is negative.

Finally, we classify pavement roughness into four levels, including excellent, good, qualified and unqualified, with the evaluation standards listed in Table I.

TABLE I. EVALUATION STANDARDS FOR PAVEMENT ROUGHNESS LEVEL

v(km/h)	RQI	Pavement roughness level
v>80	RQI>3.6	excellent
	3.0<RQI<3.6	good
	2.5<RQI<3.0	qualified
	0<RQI<2.5	unqualified
40<v<80	RQI>3.2	excellent
	2.8<RQI<3.2	good
	2.4<RQI<2.8	qualified
	0<RQI<2.4	unqualified
v<40	RQI>3.0	excellent
	2.6<RQI<3.0	good
	2.2<RQI<2.6	qualified
	0<RQI<2.2	unqualified

D. Algorithm framework

The framework of our pavement roughness level algorithm is illustrated in Figure 4.

The first step is data collection, including the data from three-axis accelerometers and GPS sensors. The second step is carried out by the PSD analyzer. The auto-correlation function will produce the PSD. The third step is carried out by the IRI analyzer. Roughness standard deviation and IRI are calculated. The fourth step is the classification of pavement roughness levels. We calculate RQI and classify pavement roughness into four levels.

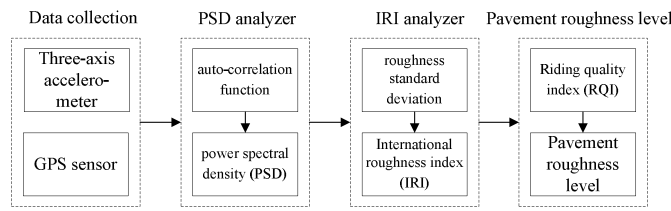


Figure 4. Pavement roughness level algorithm framework

V. EVALUATION

This section presents the evaluation of RCM-TAGPS. The experiment setting, including the road condition and the placement of our sensors, is described in details in Part A. Our pavement roughness level algorithm is implemented based on the data from field experiments in Part B. Experimental results are discussed and presented in Part C.

A. Experimental setting

As mentioned above, RCM-TAGPS depends on the accurate signals like acceleration and velocity. As a result, the accelerometers and GPS sensors must be correctly placed so that the acquired information is exact. Figure 5 shows the placement of these sensors in our experiments. The three-axis accelerometer is attached to the right side of dashboard, so that it can approach the vibrations of the driving vehicle as far as possible. Furthermore, we need place the three-axis accelerometer in a special direction, where its X-axis is with the same direction as the driving direction, its Y-axis in the corresponding horizontal direction and the Z-axis in the corresponding vertical direction. However, the GPS sensor is fixed to the left front windshield in the lateral part of the vehicle, to obtain real-time signals in urban area.

(a) three-axis accelerometer (b) GPS sensor

Figure 5. Experimental setting of sensors

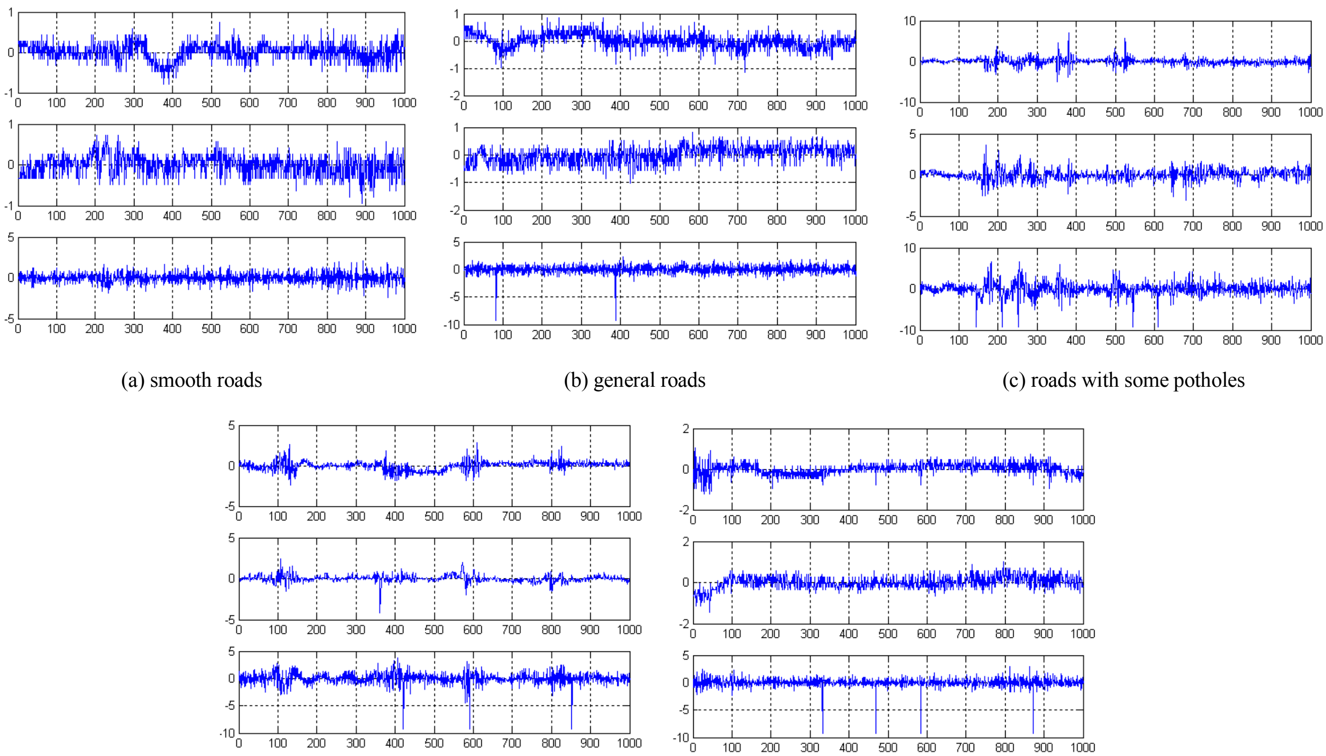
To evaluate the pavement roughness level comprehensively and effectively, we collect data from actual roads with various characters, including the following types: (I) smooth roads where the segments of road surface are considered smooth, (II) general roads where there are small particles such as sands or stones, (III) roads with some potholes, (IV) roads with some manholes, (V) roads with some decelerating belts.

We carried out hundreds of drives, and collected data by the experimental vehicles equipped with RCM-TAGPS in urban area of Beijing. The traces contain continuous acceleration and GPS data. Here, the acceleration consists of about 100 raw readings per second, while the GPS data is produced once per second, as described in Section III.

B. Evaluation

We clean the raw data with our data cleaning algorithm, including outlier removal, data interpolation and so on. It is noted that the average velocity of our experimental vehicles is normally around 40 km/h because the heavy traffic in urban area.

Figure 6 shows the continuous three-axis accelerations against the sampling points on various road types. Specially, Figure 6(a) demonstrates three-axis acceleration on smooth roads, while the others on general roads, roads with some potholes, roads with some manholes, and roads with some decelerating belts separately.



(a) smooth roads (b) general roads (c) roads with some potholes

(d) roads with some manholes (e) roads with some decelerating belts

Figure 6. The continuous three-axis accelerations on various road types

As discussed in Section III, we implement our pavement roughness level algorithm on various road types respectively. Firstly, PSD of pavement surface roughness can be presented as the Fourier transform of the auto-correlation function of three-axis acceleration. Then we analyze the roughness deviation and IRI. Finally, pavement roughness level is classified by Table I. Pavement roughness levels of various road types are listed in Table II.

TABLE II. PAVEMENT ROUGHNESS LEVELS OF VARIOUS ROAD TYPES

road type	IRI	RQI	Pavement roughness level
smooth roads	4.90	3.32	excellent
general roads	6.18	2.88	good
roads with potholes	12.33	0.79	unqualified
roads with manholes	8.24	2.18	unqualified
roads with decelerating belts	6.81	2.66	qualified

C. Experiment results

Experimental results of RCM-TAGPS are discussed as follows.

The Z-axis accelerometer should be more concerned. During the experimental drives, the X-axis is with the same direction as driving, while the Y-axis and the Z-axis are in the horizontal and vertical direction respectively. Obviously, the Z-axis has a more prominent waveform on rough pavement, which should be investigated with priority.

As illustrated in Figure 6(a), when driving on smooth roads, the acceleration data are very smoothly with only small fluctuations, so that the overall road condition is outstanding.

We infer from Figure 6(b) that there are some instantaneous large pulses in the Z-axis acceleration on general roads. It might be aroused by small particles or other interferences on the road, and the overall road condition is considered to be good.

Figure 6(c) shows the acceleration data sampled with continuous small potholes. The acceleration data are with great fluctuations, and we deduce that the vehicles vibrated strongly when passing by these potholes. The road condition is unqualified in general.

Figure 6(d) indicates the acceleration data sampled with some manholes, which is much similar to Figure 6(c). The acceleration data are also with great fluctuations, and the road condition is unqualified.

From Figure 6(e), we find there is a large pulse at certain points in the Z-axis acceleration when passing by several narrow decelerating belts. The road condition is considered to be qualified in spite of these disturbances.

VI. CONCLUSION

This paper describes the design, implementation and experimental evaluation of a road condition monitoring system, which is called RCM-TAGPS. RCM-TAGPS uses mobile vehicles embedded with a three-axis accelerometer and a GPS sensor to collect the data of three-axis acceleration and velocity with a high frequency. We clean the sampling raw data with our clean algorithm, including outlier removal, data interpolation and so on, to deal with technical challenges like unavailable GPS and transmission error. Then we analyze the Power Spectral Density (PSD) of pavement surface roughness, estimate the International Roughness Index (IRI), and classify the pavement roughness levels into four levels according to the *Technical Code of Maintenance for Urban Road CJJ36-2006*. Finally we evaluate RCM-TAGPS with actual driving in urban area of Beijing. Experimental results show that RCM-TAGPS can evaluate the pavement roughness level correctly, even with some interference like potholes, manholes and decelerating belts. Furthermore, RCM-TAGPS consumes no more than 50 dollars in total, which is only 1/4400 to 1/160 of these existing systems [4] with a cost of about 8,000 to 222,000 dollars. Therefore, RCM-TAGPS is more likely to be widely used in municipal engineering.

REFERENCES

[1] J. Eriksson, L. Girod, and B. Hull, etc. “The Pothole Patrol: Using a Mobile Sensor Network for Road Surface Monitoring”, 6th International Conference on Mobile Systems, Applications, and Services (MobiSys 2008), Breckenridge, USA, June, 2008, pp. 29-39.

[2] R. Bishop, “A survey of intelligent vehicle applications worldwide”, IEEE Intelligent Vehicles Symposium (IV 2000), Dearborn, MI, USA, May, 2000, pp. 25-30.

[3] X. Chu, and Y. Wu, “Desigend on the low cost system framwork of road conditon recgonition based on roadside multi-sensoers”, Asia-Pacific Confernce on Information Precessing (APCIP 2009), Guangdong, China, July, 2009, pp. 173-176.

[4] J. Budras, A synopsis on the current equipment used for measuring pavement smoothness. http://www.fhwa.dot.gov/pavement/smoothness/rough.cfm, August, 2001.

[5] L. Sun, “Optimum design of road-friendly vehicle suspension systems subjected to rough pavement surfaces”, Applied Mathmatical Modelling, 2002, vol. 26, pp. 635-652.

[6] L. Sun, and T. Kennedy, “Spectral analysis and parametic study of stochastic pavement loads”, Journal of Engineering Mechanics, 2002, vol. 128, pp. 318-327.

[7] Y. Zhang, and R. Ma, “A study of pavement roughness measurement system based on laser ranger finder”, International Conference on Image Analysis and Signal Processing (IASP 2009), Zhejiang, China, April, 2009.

[8] J. Dyer, D. Dyer, and J. Devore, “Estimating International Roughness Index from noisy profilograph measurements”, International Instrumentation and Measurement Technoloty Conference (I2MTC 2009), Singapore, May, 2009.

[9] R. Hostettler, W. Birk, and M. Nordenvaad, “Surface mounted vehicle property sensing for cooperative vehicle infrastructure systems”, 16th ITS World Congress and Exhibition on Intelligent Transport Systems and Services, Stockholm, Sweden, September, 2009.

[10] Y. Qing, A. Lim, and P. Agrawal, “GPSFR: GPS-free geographic routing protocol for intelligent vehicles”, International Conference on Comunications and Networks in China (Chinacom2006), Beijing, China, October, 2006, pp. 1-8.

[11] A. Thiagarajan, L. Ravindranath, and K. Lacurts, etc. “VTrack: accurate, energy-aware road traffic delay estimation using mobile phones”, 7th ACM Conference on Embedded Networked Sensor Systems (SenSys 2009), Berkeley, California, USA, November, 2009, pp. 85-98.

[12] L. Sun, “Simulation of Pavement Roughness and IRI Based on Power Spectral Density”, Mathematics and Computers in Simulation, 2003, vol. 61, pp. 77-88.

[13] D. Xu, A. Mohamed, and R. Yong, etc. “Development of a criterion for road surface roughness based on power spectral density function”, Journal of Terramechanics, 1992, vol. 29, pp. 477-486.

[14] W. Gardner, "A sampling theorem for nonstationoary random process", IEEE Transactions on Information Theory, 1972, vol. 18, pp. 808-809.

[15] L. Cohen, “Generalization of the Wiener-Khinchin theorem”, IEEE Signal Processing Letters, 1998, vol. 5, pp. 292-294.

[16] A. Fung, “A note on the Wiener-Khintchine theorem for autocorrelation”, Proceedings of the IEEE, 1967, vol. 55, pp. 594-595.

[17] T. Semiha, and A. Huseyin, “A study of random vibration characteristics of the quarter-car model”, Journal of Sound and Vibration, 2005, vol. 282, pp. 111-124.

[18] C. Dodds, and J. Robson, "The description of road surface roughness", Journal of Sound and Vibration, 1973, vol. 31, pp. 175-183.

[19] S. Lou, Y. Wang, and C. Xu, “Study of calculation of IRI based on power spectral density of pavement surface roughness”, Journal of Highway and Transportantion Research and Development, 2007, vol. 24, pp. 12-15.

[20] Y. Shucong, *Technical Code of Maintenance for Urban Road CJJ36-2006*, Beijing, China Architecture & Building Press, 2006.