Robustness Improvement of Vehicle Modeling and Kalman Filter-based Road Profile Estimation

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1. INTRODUCTION

Response-based road condition evaluation has been widely studied. DRIMS[1-2] evaluates the International Roughness Index (IRI) by modelling the measurement vehicle as either a quarter car (QC) or a half car (HC); the transfer function from this numerical model response to the golden car response is utilized to estimate IRI taking into account the dynamic characteristics of the measurement vehicle. Instead of estimating road condition index, e.g. IRI, the road profile reconstruction using statistical method based on vehicle dynamic responses has been further developed [3-4]. These methods can estimate road profile with various levels of accuracy, complexity, and computational cost. However, all of them require the dynamic properties of test vehicles to be known in advance by either a laboratory loading test or a simple model approximation. In this paper, response-based road profile estimation using multiple outputs measured by smartphone installed on ordinary vehicles is proposed. The algorithm consists of two steps. At first, the measurement vehicle is modeled as HC; its parameters are identified by genetic algorithm when vehicle drives over a known-size hump. In the second step, with the estimated vehicle model, an augmented Kalman filter is used to estimate the road profile by including the unknown road profile as a state variable. The flow chart of the proposed method is shown in Figure 1.

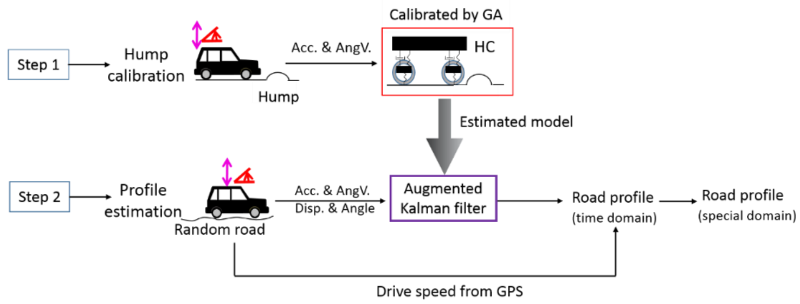

Figure 1. Flow chart of the proposed method

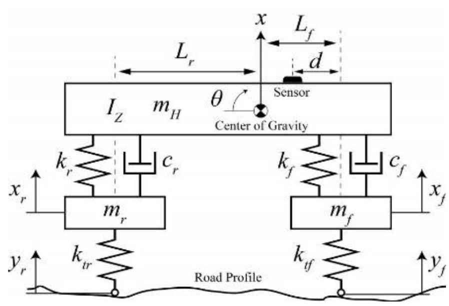

Figure 2. Half car model

2. PROFILE ESTIMATION

(1) Vehicle modelling (hump calibration)

In order to account for the differences in dynamic characteristics of vehicles, vehicles are modelled as a HC (Figure 2) and the parameters are identified through a process named hump calibration. The parameters of HC include, m_H: vehicle body mass; m_f: Front tire mass; m_r: rear tire mass; c_f : front suspension damping; c_r: Rear suspension damping; k_f : Front suspension stiffness; k_r: rear suspension stiffness; k_{tf} : front tire stiffness; k_{tr}: rear tire stiffness; I_z: Pitching moment of inertial; L_f : Distance from the center of gravity to the front axle; L: wheelbase. The equation of motion of HC is shown in Eq. (1) and (2). The vertical acceleration and pitching angular velocity of the vehicle body are measured when a vehicle passes a portable hump of a specific shape at a specific speed. Both vertical acceleration and angular velocity is measured by smartphone with an iOS application named iDRIMS [2]. During the measurement, smartphone is installed on a flat horizontal surface as shown in Figure 3. The hump is 5cm high and 30cm wide. The speed is specified to be around 10km/h. The unknown vehicle mechanical parameters in Eq. (3) are normalized by total weight and optimized using genetic algorithm (GA) in the frequency domain. The objective function to be minimized is set as the weighting summation of power spectrum density (PSD) of acceleration and angular velocity, which are normalized by their own standard deviation.

(2) Profile estimation

In the second step, the calibrated vehicle model is used to estimate road profile with the measurement of vertical acceleration and pitch angular velocity, as well as the vertical displacement and angle which are calculated from double integration of acceleration and single integration of angular velocity, respectively. The profile estimation is formulated based on a Kalman filter with an augmented state-space model, where road profile is included as a state variable (Eq.4).

$$\dot{\mathbf{x}} = \mathbf{A}_s\mathbf{x} + \mathbf{B}_s\mathbf{u} \quad \mathbf{A}_s = \begin{bmatrix} \mathbf{O}_{4\times4} & \mathbf{I}_{4\times4} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix};\ \mathbf{B}_s = \begin{bmatrix} \mathbf{O}_{4\times4} \\ \mathbf{M}^{-1} \end{bmatrix};\ \mathbf{u} = \begin{bmatrix} 0 & 0 & y_f k_{tf} & y_r k_{tr} \end{bmatrix}^T;\ \mathbf{x} = \begin{bmatrix} x & \theta & x_f & x_r & \dot{x} & \dot{\theta} & \dot{x}_f & \dot{x}_r \end{bmatrix}^T \tag{1}$$

$$\mathbf{M} = \begin{bmatrix} m_H & 0 & 0 & 0 \\ 0 & I_Z & 0 & 0 \\ 0 & 0 & m_f & 0 \\ 0 & 0 & 0 & m_r \end{bmatrix};\ \mathbf{C} = \begin{bmatrix} c_f + c_r & L_r c_r - L_f c_f & -c_f & -c_r \\ L_r c_r - L_f c_f & L_f^2 c_f + L_r^2 c_r & L_f c_f & -L_r c_r \\ -c_f & L_f c_f & c_f & 0 \\ -c_r & c_f & 0 & c_r \end{bmatrix};\ \mathbf{K} = \begin{bmatrix} k_f + k_r & L_r k_r - L_f k_f & -k_f & -k_r \\ L_r k_r - L_f k_f & L_f^2 k_f + L_r^2 k_r & L_f k_f & -L_r k_r \\ -k_f & L_f k_f & k_f + k_{tf} & 0 \\ -k_r & -L_r k_r & 0 & k_r + k_{tr} \end{bmatrix} \tag{2}$$

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$$\left[k_f \quad k_r \quad c_f \quad c_r \quad k_{tf} \quad k_{tr} \quad L_f \quad m_H \quad m_f \quad I_z\right] / m_{total} \tag{3}$$

$$\mathbf{x}_{kal} = \left[x \quad \theta \quad x_f \quad x_r \quad \dot{x} \quad \dot{\theta} \quad \dot{x}_f \quad \dot{x}_r \quad y_f \quad \dot{y}_f \quad y_r \quad \dot{y}_r\right]^T \tag{4}$$

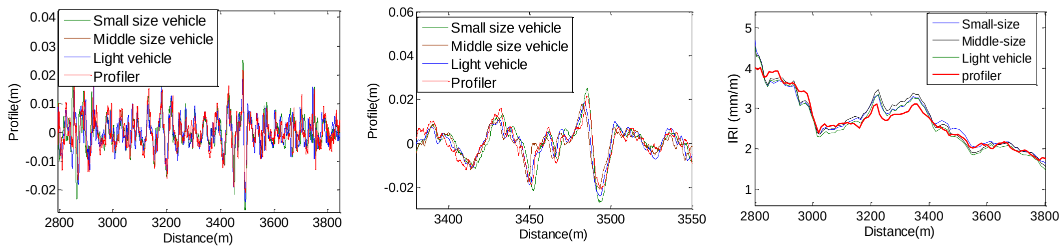
3. EXPERIMENTAL VALIDATION

Field test is performed on an ordinary road in Chiba city, Japan. In order to investigate the applicability of the proposed methods, three different types of vehicles are tested. These vehicles are a light vehicle, a small size vehicle, and a middle size vehicle, as shown in Figure 4 (a-c). Each vehicle is installed with multiple iPod touch devices allowing different sensor locations along the longitudinal direction including the dashboard, front and rear passenger seat floors, and trunk. The profile estimation accuracy of the proposed method is examined by comparing the estimates with a reference obtained by a laser profiler, as shown in Figure 4 (d). The profile comparisons of three vehicles (dashboard sensor) and profiler are shown in Figure 5 (a-b).

Figure 3. sensor installation

(a) Light vehicle (b) Small size (c) Middle size (d) Profiler

Figure 4. Experimental vehicles



(a) 1km profile estimation (b) Zoom in (c) IRI

Figure 5. Profile estimation performance

Table 1. IRI error (1km)

light	6.9%
small	6.6%
middle	7.1%

As shown in Figure 5 (a-b), the profile estimation using three ordinary vehicles show good agreement overall with the profiler measurement. The accuracy of profile estimation is quantified by the IRI, as shown in Figure 5 (c). The relative IRI error between three vehicles and road profiler are shown in Table 1. All the vehicles show IRI relative error smaller than 10%, which indicates that the proposed method can estimate road profile with fairly high accuracy.

5. CONCLUSION

Methods of vehicle modelling and road profile estimation are proposed. In the vehicle modelling, a half car model is optimized by genetic algorithm when vehicle passes a known size hump. Road profile is then estimated by using an augmented Kalman filter and the estimated half car model. Experiment at an ordinary road is conducted by comparing three types of vehicles and a laser based profiler as a reference. The relative IRI error between the estimations and profiler indicates that the proposed method can accurately evaluate road profile by using responses in ordinary vehicles.

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6. REFERENCE

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