Estimation of Driver's Steering Intention by Using Mechanical Impedance

Takafumi Asao, Satoshi Suzuki, and Kentaro Kotani

Faculty of Engineering Science, Kansai University, Japan
{asao,ssuzuki,Kotani}@kansai-u.ac.jp

Abstract. We attempted to estimate a driver's steering intention by using human mechanical impedance, which changes as a result of muscle activity, because humans should be ready to act before moving. First, we verified the estimated accuracy of the impedance under a static condition. The estimation results showed good accuracy. Then, we tried to estimate the time-varying human impedance during a tracking task using the steering wheel. There were some instances where the stiffness became high before steering and became low after steering, but the occurrence rate was low.

Keywords: steering intention, mechanical impedance, dynamic identification, Kalman filter.

1 Introduction

Driving support systems have been developed to take the place of a portion of a driver's cognition, judgment, and operation [1]. However, there could be conflicts between the driver's intentions and those of the system if such systems become popular and cover various situations [2]. Drivers hope that such systems will not be bothersome, but will have properly designed support timing and functions.

The information required by these systems is divided into vehicle information, environmental information, and driver information. The vehicle information consists of dynamic data about the vehicle such as its position and slip angle. The environmental information includes the road alignment and the positions of other vehicles and pedestrians, as identified using various sensors. The driver information consists of the driver's operational and physiological data. Almost all of the existing systems utilize only vehicle and environmental information. However, using the driver information in addition to the vehicle and environmental information is necessary to ensure that such systems support drivers with appropriate timing, rather than becoming bothersome. If the driver's intention can be estimated, it will be possible to support the driver after determining the adequacy and safety of the driver's operation, while coordinating the vehicle, environmental, and driver information.

Some previous studies tried to estimate a driver's steering intention by using an electroencephalogram (EEG) and eye movements [3], [4]. Ikenishi et al. proposed an algorithm to estimate the steering intentions, which were going straight, turning right, or turning left, using the power spectrum (8 to 30 Hz) of a background EEG [3].

S. Yamamoto (Ed.): HIMI/HCII 2013, Part I, LNCS 8016, pp. 3–11, 2013.

Suzuki et al. attempted to estimate a driver's intention to change lanes (to the right) on a highway by using the driver's eye movements [4]. Performing EEG measurements in a moving vehicle has two problems. There is background noise in the EEG signals as a result of the body movements of the driver, vehicle vibration, and electric components of the vehicle. Drivers are constrained by the attached EEG electrodes. On the other hand, the eye tracking system, which has high resolution, is not applicable because of the cost.

Humans can move their arms, legs, and body in response to some task. They configure an appropriate mechanical impedance by adjusting their musculo-viscoelasticity before the movement [5], [6]. Impedance is a collective term for the inertia, viscosity, and stiffness, which constitute the motion resistance [5]. Humans raise the stiffness and viscosity of their hands in order to start moving quickly in the desired manner [6]. This study focused on the impedance in a driver's hands while grasping the steering wheel. The goal of this study was to estimate a driver's steering intentions by using the impedance. In this paper, we try to estimate the impedance dynamically and verify that the steering intention can be estimated from the impedance.

2 Identification of Impedance

2.1 Selection of Identification Technique

Studies on human impedance began with Mussa-Ivaldi, Hogan, & Bizzi (1985). They measured the stiffness of a human hand [7]. After that, impedance measurements were extended to include the viscosity and stiffness [8], [9], [10]. In these studies, perturbation was given to the hand for a very short duration in order to prevent changes in the impedance as a result of human voluntary reaction. This technique can only be applied to measure the impedance for static postures. Therefore, an ensemble method was devised, by which the impedance at any time could be estimated by using a large quantity of static single trial data [11], [12], [13]. In recent years, an online estimation technique has been developed in order to estimate the time-varying impedance during movements by using a frequency filter to remove the voluntary constituent [14], [15].

Shin et al. proposed a dynamic estimation method by using an electromyogram (EMG) and musculo-mechanics, in which an EEG was considered to represent the commands from the brain [16]. Hada et al. developed a dynamic estimation method by using a musculo-skeletal model and kinematics, in which muscular activations were estimated from measured sequential posture data [17].

The online method, muscular model method, and musculo-skeletal model methods should be suitable to estimate the steering intention, because the impedance is time-varying. However, the muscular model method is not recommended because of the restraints imposed by the EMG electrodes that have to be attached to the driver. The musculo-skeletal model method would also be unsuitable, because measuring driving postures is difficult at high resolution. Therefore, this study employed the online estimation method, with which the impedance could be estimated using only the steering wheel angles and torques.

2.2 Impedance Model for Human-Steering System

The equation of motion for a steering wheel is represented as

$$M_s\ddot{\theta} + B_s(\dot{\theta} - \dot{\theta}_e) + K_s(\theta - \theta_e) = \tau + \tau_h \tag{1}$$

where M_s, B_s, and K_s denote the rotational inertia, viscosity, and stiffness of the structural elements of the steering system, respectively. θ and θ_e denote the steering wheel angle and its equilibrium angle, respectively, and τ and τ_h denote the torques applied by a motor and human, respectively. The equation of motion for a human in relation to the steering wheel shaft is represented as

$$M_h\ddot{\theta} + B_h(\dot{\theta} - \dot{\theta}_e) + K_h(\theta - \theta_e) = -\tau_h \tag{2}$$

where M_h, B_h, and K_h denote the equivalent rotational impedance factors of the human. From Eqs. (1) and (2), the equation of motion for the human-steering system is represented as

$$M\ddot{\theta} + B(\dot{\theta} - \dot{\theta}_e) + K(\theta - \theta_e) = \tau \tag{3}$$

where $M = M_s + M_h$, $B = B_s + B_h$, and $K = K_s + K_h$ are the impedance factors for the human-steering system, which are time-varying because M_h, B_h, and K_h are time-varying.

A situation where a single perturbation is applied to the steering wheel by a motor connected to the steering shaft is considered. The torque changes from τ to $\tau + \Delta\tau$, and the angle changes from θ to $\theta + \Delta\theta$. Then, the following two conditions are assumed:

(1) The human arm posture and impedance do not change before and after the perturbation because the perturbation is small [7], [18].
(2) The human cannot change their impedance, equilibrium point, and force against the perturbation because the duration of the perturbation is short [18].

Based on these assumptions, the equation of motion for the human-steering system after the perturbation is represented as

$$M(\ddot{\theta} + \Delta\ddot{\theta}) + B(\dot{\theta} + \Delta\dot{\theta} - \dot{\theta}_e) + K(\theta + \Delta\theta - \theta_e) = \tau + \Delta\tau \tag{4}$$

If the frequency of human movement is considerably smaller than that of the perturbation, the human involuntary motion can be obtained, as shown in the following equation, by band-pass filtering the measured angle and torque [14], [15].

$$M\Delta\ddot{\theta} + B\Delta\dot{\theta} + K\Delta\theta = \Delta\tau \tag{5}$$

This equation can be applied to both a single perturbation and continuous perturbation.

2.3 Impedance Estimation Algorithm by Kalman Filter

This section shows the impedance estimation method. The time-varying variables from the previous section are represented with sampling number i as discrete variables. The impedance and variables are defined as vectors:

$$\boldsymbol{U}_i = \begin{bmatrix} M_i & B_i & K_i \end{bmatrix}^T \tag{6}$$

$$\boldsymbol{\theta}_i = \begin{bmatrix} \Delta\ddot{\theta}_i & \Delta\dot{\theta}_i & \Delta\theta_i \end{bmatrix}^T \tag{7}$$

The parameter $\boldsymbol{U}$ is estimated using the following updating equations:

$$\boldsymbol{k}_i = \frac{P_{i-1}\boldsymbol{\theta}_i}{\lambda + \boldsymbol{\theta}_i^T P_{i-1}\boldsymbol{\theta}_i} \tag{8}$$

$$P_i = P_{i-1} - \boldsymbol{k}_i\boldsymbol{\theta}_i^T P_{i-1} \tag{9}$$

$$\boldsymbol{U}_i = \boldsymbol{U}_{i-1} + \boldsymbol{k}_i\left(\Delta\tau_i - \boldsymbol{\theta}_i^T\boldsymbol{U}_{i-1}\right) \tag{10}$$

where $\boldsymbol{k} \in R^3$, $\lambda \in R$, and $P \in R^{3\times3}$ denote the Kalman gain, variance of the observation noise, and covariance matrix, respectively. ^{T} denotes transposing the vector or matrix. The initial values are set at

$$\boldsymbol{U}_0 = \boldsymbol{0} \tag{11}$$

$$P_0 = \mathrm{diag}\left(10^4, 10^4, 10^4\right) \tag{12}$$

where the diag operator indicates a diagonal matrix. λ is set at 0.8.

3 Verification Experiment for Estimation Accuracy

Before estimating the human impedance, an experiment was conducted to verify the estimation accuracy by using known parameters.

3.1 Apparatus

Fig. 1 shows an illustration of the apparatus. The outer diameter of the steering wheel (Nardi classic) was 360 mm. The steering wheel shaft was connected to an AC servomotor (SGMPH-08A1A41, Yasukawa Electric Corp.) via a high stiffness coupling. The torque of the motor was controlled by a PC via a D/A board and motor driver, which allowed it to generate perturbations. The steering wheel angle was measured using an incremental encoder in the motor unit (65536 pulse/rev). In this experiment, the equipment was placed on the floor because the rotational plane of the steering wheel was vertical. The steering wheel angles and command torque were measured by the PC at a 100-Hz sampling frequency.

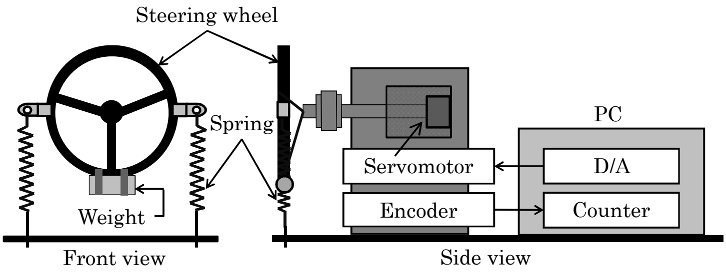

Fig. 1. Illustration of experimental system

3.2 Perturbation

The perturbation torque that was necessary for estimating the impedance was an M-sequence signal with the condition that a primitive polynominal was $x^7 + 1$. The 0 and 1 signals created by the M-sequence were assigned values of –0.5 or +0.5 Nm, respectively. The torque was changed at intervals of 30 ms because of the created signals. Thus, the cycle length of the perturbations was 3.81 s.

3.3 Experimental Conditions

Weights were attached to the bottom of the steering wheel, whose mass and shape were known. Two different weights were used, 0.5 and 1.0 kg, whose moments of inertia about the steering wheel axis were 1.9×10^{-2} and 4.1×10^{-2} kg·m^2, respectively. A set of two identical springs were vertically attached to the sides of the steering wheel, with their ends clamped to the floor. The spring constants of two different sets of springs were 114 and 458 Nm. The converted rotational stiffness values at the tangent of the steering wheel were 4.55 and 18.3 Nm/rad, respectively. There were a total of nine conditions for the various combinations of three weights (including no weight) and three springs (including no spring). The measuring duration for each condition was 15.24 s, which was four cycles of the M-sequence signals. Ten trials were conducted for each condition. Because the impedance of this system was invariant, the impedance was estimated using the least square method (LSM) from Eq. (5), in addition to the recursive Kalman filter method described in Eqs. (8) to (10). The measured data were preprocessed by using a fourth-order band-pass Butterworth filter whose cut-off frequencies were 5 and 20 Hz.

3.4 Experimental Results

Fig. 2 shows an example of the estimated results for the conditions of a heavy weight and weak spring. In the figures, the thick lines denote the impedance estimated by the Kalman filter, and the thin lines denote that by LSM. The impedances estimated by using the Kalman filter increased rapidly, because the initial values of the impedance were set to zero. On the other hand, the impedance estimated by the Kalman filter became the same as that by LSM over time. Therefore, in this section, the impedance found by LSM is discussed.

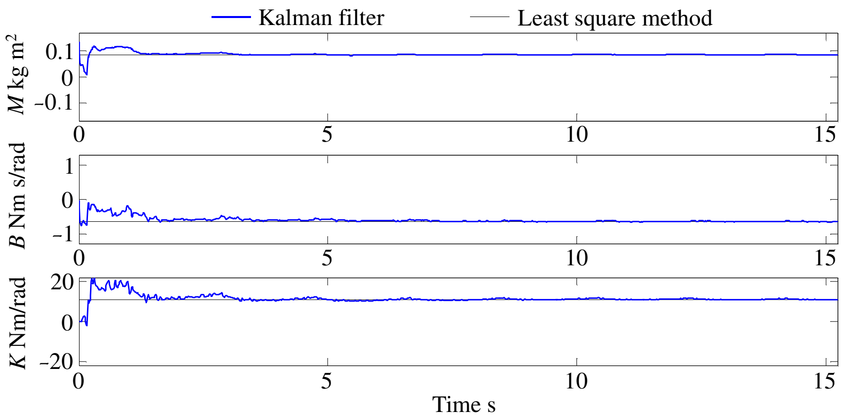

Fig. 2. Example of estimated impedances for condition of heavy weight and weak spring

Figs. 3 and 4 show the mean inertia and stiffness estimated by LSM with error bars for standard deviations, respectively. The structural impedance M_s and K_s could be obtained under the no weight and no spring condition. The structural impedance was subtracted from the values in the figures. The crossbars in the figures denote the given impedances. The estimated impedances increased with the given impedance. The estimated values were almost the same as the given ones. Therefore, the values estimated by the Kalman filter had good accuracy.

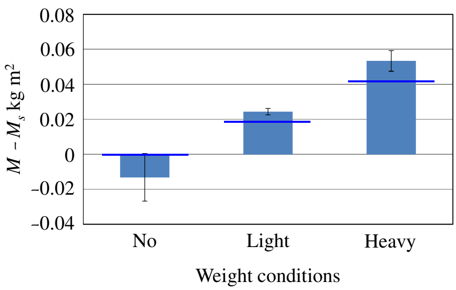

Fig. 3. Estimated inertia for validation

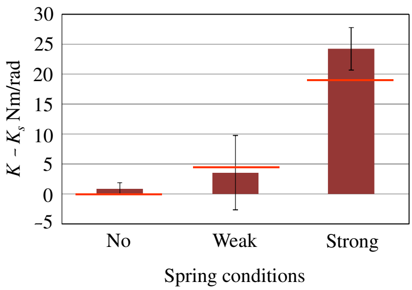

Fig. 4. Estimated stiffness for validation

4 Human Impedance during Steering Operation

4.1 Experimental Conditions

Fig. 5 shows a scene of the experiment. The subjects tracked a visual target using a steering wheel while sitting in the driver's seat. As shown in Fig. 6, a red square as the tracking target and operable black cross coupled to the steering wheel were shown on a CRT. The target moved laterally for a quarter cycle according to a sine wave. The subjects operated the steering wheel to prevent the operable target from deviating from the tracking target. The amplitude of the tracking target was set to 40, 80, or 120°. The frequency of the tracking target was set to 0.3, 0.5, or 0.7 Hz. The subjects were four healthy male university students.

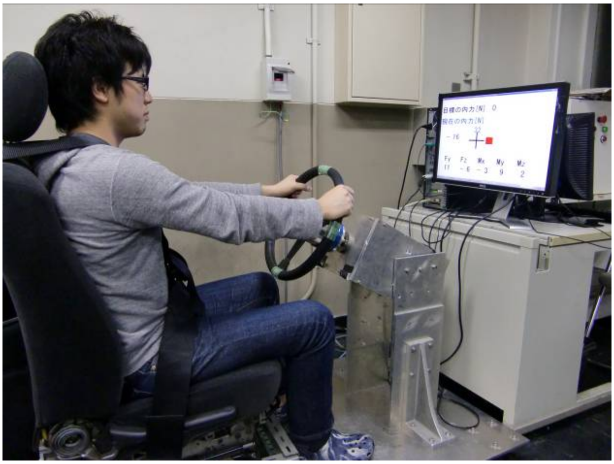

Fig. 5. Overview of tracking experiment

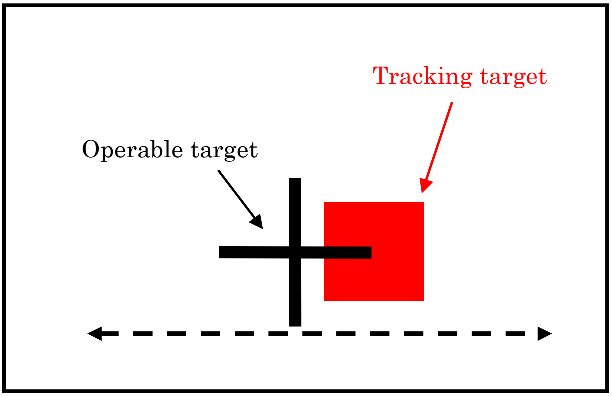

Fig. 6. Displayed screen image

4.2 Results and Discussions

Fig. 7 shows the estimated impedance for subject D under the condition of a 120° amplitude and frequency of 0.7 Hz. Each figure in Fig. 7 represents the steering angle, inertia, viscosity, and stiffness in order from the top. The red dashed lines cutting the figures longitudinally denote the moment at which the target started to move. The viscosity when the steering angle is almost at zero is higher than that for the other values. Moreover, as shown by the circles in the figure, there were some instances where the stiffness became high before steering and became low after steering. However, this did not occur in every case. This may have been affected by muscle contraction. Therefore, the muscle activity should be measured and validated. On the other hand, the pressure when gripping the steering wheel should not be constant. Whether or not the muscle stiffness changed, the gripping pressure affected the estimated impedance. In other words, the estimated impedance included the muscle stiffness and gripping state. If humans try to steer, the gripping force may change. Therefore, the steering intention could be estimated by using not only the muscle stiffness but also the gripping force.

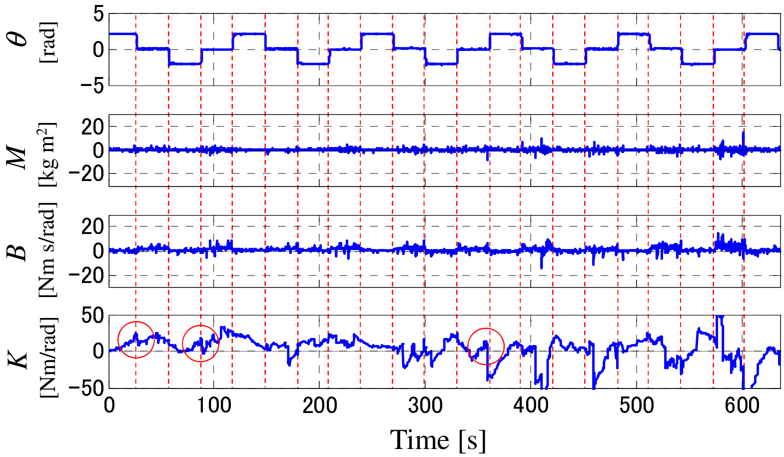

Fig. 7. Estimated human impedance

5 Conclusion

In this study, we attempted to estimate a driver's steering intention by their impedance. First, we verified the accuracy of the impedance estimated by using a Kalman filter. The estimation method was found to have good accuracy. Then, we tried to estimate the time-varying human impedance during a tracking task using a steering wheel. There were some instances where the stiffness became high before steering and became low after steering, but the occurrence rate was low. The factors that led to this occurrence were unknown. Therefore, in future work, we will verify the muscle activity and gripping force during the steering operation. Moreover, the estimation model, that is, the Kalman filter, will be improved in order to improve the estimation accuracy.

References

1. Tsugawa, S.: Current Status and Issues on Safe Driver Assistance Systems. Journal of Society of Automotive Engineers of Japan 63(2), 12–18 (2009)
2. Inagaki, T.: Humans understand machines; machines understand humans. In: Proceedings of 16th Annual Meetings of JSME Transportation and Logistics Division, pp. 7–10 (2007) (in Japanese)
3. Ikenishi, T., Machida, Y., Kamada, T., Nagai, M.: Estimation of Driver Steering Intention based on Brain-Computer Interface using Electroencephalogram. Transactions of Society of Automotive Engineers of Japan 39(6), 23–28 (2008)
4. Suzuki, M., Inagaki, S., Suzuki, T., Hayakawa, S., Tsuchida, N.: Estimation of Switching Point in Human Driving Behavior Based on Eye-movement and Bayesian Estimation. In: Proceedings of Industrial Instrumentation and Control Meeting, IIC-07-75, pp. 29–34 (2007)
5. Ito, K.: Bodily wisdom thesis as system, pp. 76–81. Kyoritsu, Kyoto (2005) (in Japanese)
6. Kim, J., Sato, M., Koike, Y.: Human arm posture control using the impedance controllability of the musculo-skeletal system against the alteration of the environments. Transactions on Control, Automation, and Systems Engineering 4(1), 43–48 (2002)
7. Mussa-Ivaldi, F.A., Hogan, N., Bizzi, E.: Neural, Mechanical, and Geometric Factors Subserving Arm Posture in Humans. Journal of Neuroscience 5(10), 2732–2743 (1985)
8. Tsuji, T.: Measurement of upper arm flexibility. Journal of Society of Instrument and Control Engineers 35(9), 689–695 (1996) (in Japanese)
9. Dolan, J.M., Friedman, M.B., Nagurka, M.L.: Dynamic and Loaded Impedance Components in the Maintenance of Human Arm Posture. IEEE Transactions on Systems, Man, and Cybernetics 23(3), 698–709 (1993)
10. Tsuji, T., Morasso, P.G., Goto, K., Ito, K.: Human Hand Impedance Characteristics during Maintained Posture in Multi-Joint Arm Movements. Biological Cybernetics 72(6), 475–485 (1995)
11. Bennett, D.J., Hollerbach, J.M., Xu, Y., Hunter, I.W.: Time-varying stiffness of human elbow joint during cyclic voluntary movement. Experimental Brain Research 88(2), 433–442 (1992)
12. MacNeil, J.B., Kearney, R.E., Hunter, I.W.: Identification of time-varying biological systems from ensemble data. IEEE Transactions of Biomedical Engineering 39(12), 1213–1225 (1992)
13. Gomi, H., Kawato, M.: Human arm stiffness and equilibrium-point trajectory during multijoint movement. Biological Cybernetics 76(3), 163–171 (1997)
14. Xu, Y., Hollerbach, J.M.: Identification of Human Joint Mechanical Properties from Single Trial Data. IEEE Transactions on Biomedical Engineering 45(8), 1051–1060 (1998)
15. Deng, M., Gomi, H.: Robust Estimation of Human Multijoint Arm Viscoelasticity during Movement. Transactions of Society of Instrument and Control Engineers 39(6), 537–543 (2003)
16. Shin, D., Shimada, O., Sato, M., Koike, Y.: Arm stiffness estimation using mathematical model of musculo-skeletal system. Transactions of the Institute of Electronics, Information and Communication Engineers J87-D-II(9), 1860–1869 (2004)
17. Hada, M., Yamada, D., Miura, H., Tsuji, T.: An Equivalent Impedance Characteristics Analysis System for Human-machine Systems. Transactions of Society of Instrument and Control Engineers 42(9), 1083–1091 (2006)