A Framework of Autonomous Electric Vehicle with Advanced Motion Control Based on the Integration of GPS Receiver and On-board Dynamic Sensors

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ABSTRACT

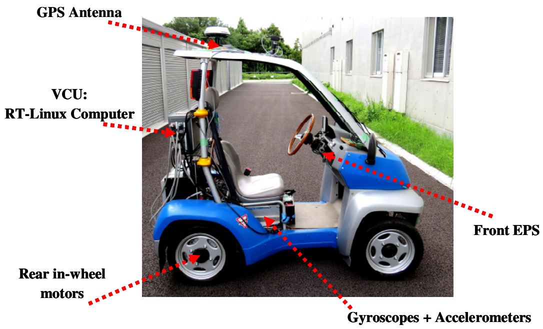
This paper presents a framework of autonomous electric vehicle utilizing advanced motion control. In order to achieve the long-term stability and accuracy in vehicle state estimation, Kalman filter is applied to combine the advantages of GPS and dynamic sensors. The framework is the integration of different local controls, such as lateral stability control, wheel slip ratio control, attitude control… In order to assure the robustness of the control system, robust control theory is applied. The effectiveness of the proposed control system is verified by various experiments.

Keywords: Electric vehicle, Global positioning system, Motion control, Autonomous vehicle.

1. INTRODUCTION

In order to reduce carbon emissions and the dependence on fossil fuel, it is essential to develop electric vehicles (EVs) to replace the internal combustion engine vehicles. From the view of motion control, EVs have a lot of advantages. Two remarkable features for advanced motion control are the quick and precise torque response and the ability of direct yaw moment generation by in-wheel motors [1].

From literature review, autonomous vehicle has been popularly researched [2-3]. However, current researches on autonomous vehicle focus on path planning, path tracking, and obstacle avoidance. The safety problem from the view of dynamic motion control is still an open topic. Therefore, we propose a framework of autonomous EV utilizing advanced motion control of EV for future transportation. This framework includes various local controls, such as path tracking control, attitude control, lateral traction control, longitudinal traction control, and velocity control. Two main issues still remain in motion control design of EVs. The first is how to accurately obtain the vehicle state in real time by using estimator or observer because



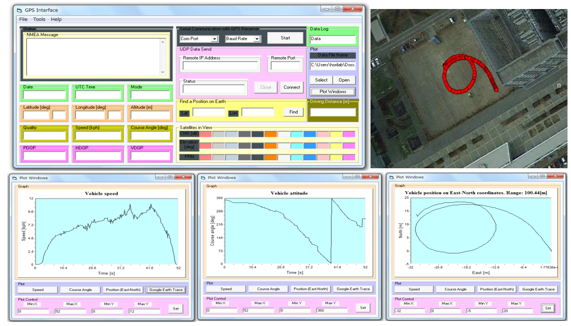


Figure 1. Experimental EV. **Figure 2. Interface of GPS software.**

a lot of motion sensors are very expensive for installation into commercial vehicles. The second is how to assure the robustness vehicle control system under the model uncertainties, the change of road condition, and the influence of strong external disturbances.

For several years, the application of GPS for vehicle dynamics control has been studied [4], [5], [10]. Dynamics sensors like gyroscopes and accelerometers can output high rate measurements but are affected by strong noise, bias, and drift. GPS data can be a source of long-term stability measurement, but at low update rate. Thus, stable and accurate vehicle state estimation can be achieved by the fusions of GPS data and dynamics sensors.

In this paper, instead of multiple antenna GPS system, single antenna GPS is used for vehicle state estimation to keep the affordable cost of the control system. Kalman filter is developed for combining GPS and on-board dynamic sensors. Robust control theory, including disturbance estimation-rejection, and sliding mode control, is applied to design the integrated system. Various experiments are conducted to verify the proposed system; several recent results are introduced in this paper.

2. EXPERIMENTAL SYSTEM AND VEHICLE MODELLING

To verify the proposed control system, a micro in-wheel motored EV named “Super-capacitor COMS” developed by EV team of Hori-Fujimoto Laboratory is used (Fig. 1). The vehicle is powered by super-capacitor instead of conventional batteries for the quick charging feature. Two in-wheel motors are placed in the rear-left and rear-right wheels. Thus, torque command can be distributed independently to generate the yaw moment. Active front steering system is used as another control actuator which can conduct the steer-by-wire mode. Gyroscope and accelerometers at the center of gravity are used to measure yaw rate, longitudinal acceleration, and lateral acceleration. A noncontact optical sensor produced by Corrsys-Datron is used for accurate acquisition of vehicle sideslip angle, longitudinal velocity, and lateral velocity. In this study, it is only used for evaluating the estimation algorithms. Estimation and control algorithms are implemented in a RT-Linux operating system computer. The basic control period of the system is 1 millisecond. GPS receiver Hemisphere R320 is used in this study. It can measure not only vehicle positioning, but also course angle, and velocity. It outputs the data in NMEA-0183 protocol at maximum rate of 20 Hz. In case of satellite based DGPS

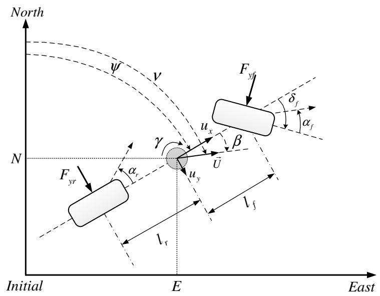


Figure 3. Lateral dynamic model.

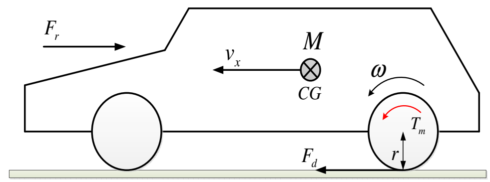


Figure 4. Longitudinal dynamic model.

model, R320's positioning accuracy is less than 1 meter. One centimeter accuracy level can be achieved under the real time kinematic mode (RTK). GPS navigation software (Fig. 2) is developed with the following main functions:

1) Decoding of the NMEA messages and display the navigation data.

2) Transferring of the motion measurement data to the RT-Linux computer through LAN cable.

3) Recording the experimental data.

Two following model are constructed to be used in this study. The first is the linear bicycle model, under the assumption that the EV is symmetric about the fore-and-aft center line; the load transfer, roll motion, and pitch motion are neglected (Fig. 3). Course angle obtained from GPS represents the sum of heading angle (yaw angle) and sideslip angle. The longitudinal dynamic model is shown in Fig. 4.

3. INTEGRATED CONTROL SYSTEM OF ELECTRIC VEHICLES

The proposed control system is shown in Fig. 5 including five layers. The most important layer is state estimation layer. In [4], double antenna GPS receiver is used to calculate sideslip angle and yaw angle directly. In this paper, by combining course angle from single antenna GPS receiver and yaw rate measurement, sideslip angle and yaw angle can be estimated using Kalman filter. The estimator layer also provides the high rate estimation of vehicle position in North-East coordinates, longitudinal, and lateral velocities.

In the autonomous control layer, the path tracking control compares the estimated positions with the desired positions to calculate the yaw angle command. Based on the difference between the command and estimated value of angle, the heading controller generates the front steering angle command.

The dynamics control layer includes lateral stability control, wheel slip ratio control, and velocity control. In order to improve the lateral stability of EV, lateral traction control is to track the sideslip angle with reference values by using the yaw moment generated by in-wheel motors. In [6], a lateral stability control scheme for EV using GPS is proposed. Wheel slip ratio control l is designed for the adhesion improvement to prevent vehicle slip on low friction road. In this study, sliding mode theory is applied to design the wheel slip ratio control. The

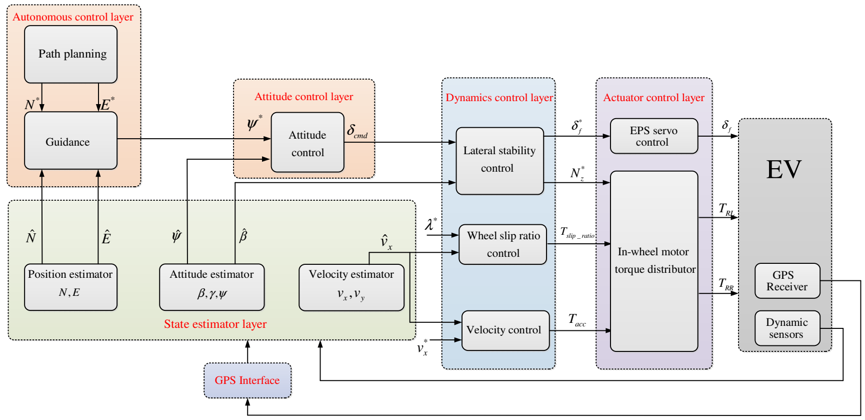


Figure 5. EV control system based on the fusion of GPS and dynamic sensors.

purpose of this local control is to generate the traction torque command. Another local control, velocity control is designed based on the velocity estimator.

The actuator control layer contains the EPS servo control system to generate the front steering angle by steer-by-wire mode. Based on the yaw moment command, wheel slip ratio control's torque command, and acceleration command, torque distribution to the rear-left and rear-right in-wheel motors are calculated.

In the following sections, several recent results of each control layer are demonstrated.

4. VEHICLE STATE ESTIMATION USING KALMAN FILTER

4.1 Kalman filter algorithm for sensor fusion

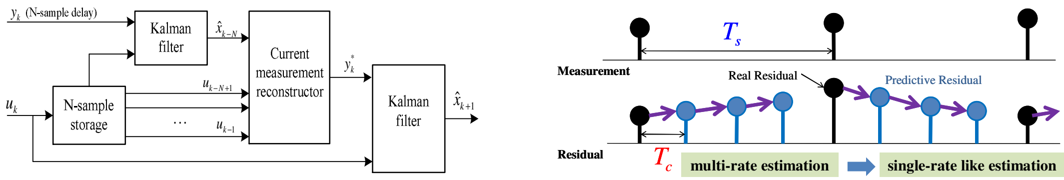
By decoding the NMEA messages from GPS receiver, the following motion measurements of vehicle can be obtained: 1) Vehicle positions in North-East coordinates. 2) Vehicle course angle. 3) Vehicle velocity vector. By fusing these low-update-rate data with the high-update-rate data from other dynamics sensor, high-update-rate and long-term-stability vehicle states are achieved. Kalman filter algorithm is developed as follows.

- **State augmentation for disturbance/sensor bias estimation**

GPS model can be combined with vehicle dynamics model or vehicle kinematic model for establishing the Kalman filter estimation. The disturbances that interferes the dynamics model, and the sensor bias in kinematic model can be augmented as extended states to be estimated. The dynamics of the extended states can be assumed to be random walk process. By this method, the accuracy of state estimation is improved. In [6], we applied this idea in EV stability control system based on sideslip angle estimation using GPS and yaw rate sensor.

- **Handling of GPS measurement delays**

RTK-GPS receiver has high accuracy measurement whose time delays are neglectable. If RTK-mode is unavailable (or a low cost GPS receiver is used), the delay of measurements from GPS is a problem to handle. The serious delay in sensor measurements will degrade the accuracy of state estimation. We proposed a Kalman filter scheme with the reconstruction of



(a) **(b)**

Figure 6. Development of Kalman filter

(a) Handling of delay measurement.

(b) Prediction of inter-sample measurement residual.

delay measurement in present time to solve this problem (Fig. 6(a)). The general formulation of the reconstruction is expressed as follows:

$$y_k^* = C_d\left(A_d^N \hat{x}_{k-N} + \sum_{j=1}^{N} A_d^{N-j} B_d u_{k-N+j-1}\right) \tag{1}$$

- **Prediction of inter-sample residuals of GPS measurements**

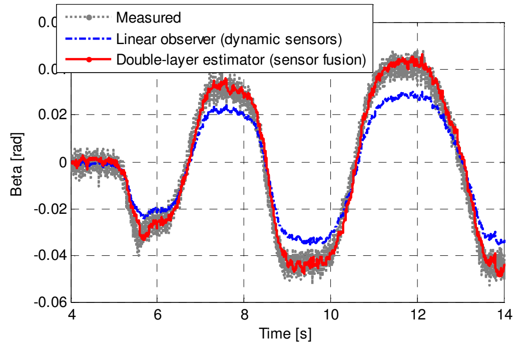
The samples between two consecutive updates of GPS data are named inter-samples in this study. In conventional Kalman method, during inter-samples, the states are corrected by using the residuals of high-rate sensors (yaw rate sensor or acceleration sensors). In [11], we proved that by predicting the inter-sample residuals of GPS measurement, the accuracy of state estimation is enhanced (Fig. 6(b)).

4.2 Several results of vehicle estimation

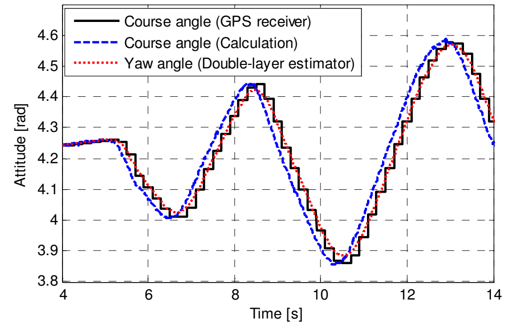
In this paper, the estimation results of yaw angle, sideslip angle, longitudinal, and lateral velocity are demonstrated. A "double-layer state estimator" based on Kalman filter is designed to provide the above key states for vehicle motion control. The first layer combines course angle from GPS and yaw rate from gyroscope to estimate yaw angle and sideslip angle. Using estimated sideslip angle and velocity vector obtained by GPS, longitudinal and lateral velocities are calculated at the update rate of GPS receiver. The second layer combines these calculated values with the measurement of accelerometers to estimate the vehicle velocities at high rate. The following model is used to establish the estimation in the first layer.

$$\begin{cases} \begin{bmatrix} \dot{\beta} \\ \dot{\gamma} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \\ \psi \end{bmatrix} + \begin{bmatrix} b_{11} & 0 \\ b_{21} & b_{22} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_f \\ N_z \end{bmatrix} \\ \begin{bmatrix} \gamma_{gyro} \\ v_{GPS} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \\ \psi \end{bmatrix} \end{cases} \tag{2}$$

The components of the dynamic matrices are obtained from vehicle parameters.



(a)



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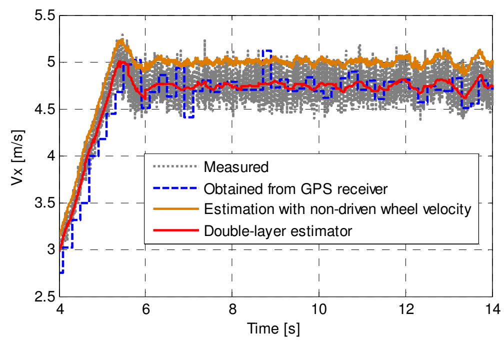
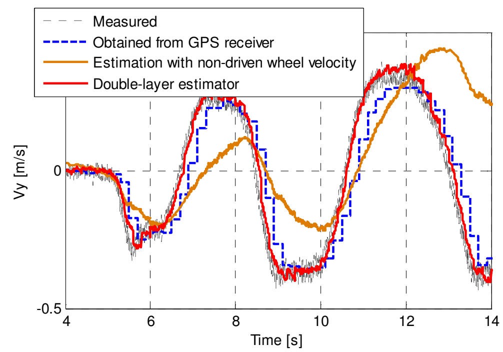


(c)



(d)

Figure 7. Experiment results of vehicle state estimation.

(a) Sideslip angle. (b). Yaw angle. (c). Longitudinal velocity. (d). Lateral velocity.

$$
\begin{aligned}
&a_{11} = -\frac{2\left(C_f + C_r\right)}{mu_x}, a_{12} = -1 - \frac{2\left(C_f l_f - C_r l_r\right)}{mu_x^2} \\
&a_{21} = -\frac{2\left(C_f l_f - C_r l_r\right)}{I_z}, a_{22} = -\frac{2\left(C_f l_f^2 + C_r l_r^2\right)}{I_z u_x} \\
&b_{11} = \frac{2C_f}{mu_x}, b_{21} = \frac{2C_f l_f}{mu_x}, b_{22} = \frac{1}{I_z}
\end{aligned}
\tag{3}
$$

Where C_f and C_r are cornering stiffness of front and rear wheels; m is vehicle mass; I_z is yaw moment of inertia; l_f and l_r are the distances from center of gravity to the front and rear axels; u_x is the longitudinal velocity.

Results of sideslip angle estimation are demonstrated in Fig. 7 (a). Another sideslip angle estimation method using dynamic sensors is performed for comparison. This method was proposed based on linear observer using yaw rate and lateral acceleration [12]. The cornering stiffness according to road condition is approximately $C_f = C_r \approx 7000$ (N/rad). The nominal cornering stiffness of each estimation method is intentionally set as $C_{fn} = C_{rn} = 10{,}000$ (N/rad) to introduce model uncertainties. In order to simulate the low cost GPS receiver, the data from RTK GPS receiver is delayed 100 milliseconds. The estimation results show that the linear observer is sensitive to model error. In contrast, by using the fusion of GPS and gyroscope, the proposed method can provide sideslip angle with much smaller estimation error. Fig. 7 (b) illustrates the estimation of yaw angle at high rate in comparison with the low rate course angle obtained from only GPS.

The estimation results of longitudinal and lateral velocities are shown in Fig. 7 (c) and (d), respectively. Based on kinematic relationship, a Kalman filter was designed for estimating vehicle velocity [12]. According to this method, the non-driven wheel's velocity is used as the approximate measurement of EV's longitudinal velocity while longitudinal and lateral accelerations are inputs of Kalman filter. Using this method, estimated longitudinal velocity is almost closed to the measured value. However, under measurement noise and bias, the estimation error of lateral velocity increases considerably. Using the proposed method, time delay of measurement from GPS is handled, and both longitudinal and lateral velocities are accurately estimated.

5. LONGITUDINAL TRACTION BASED ON SLIDING MODE CONTROL

If slip happens, vehicle may experience a serious accident. In order to prevent the slip phenomenal, wheel slip ratio control is selected. For the sake of simplicity, one-wheel model in Fig. 4 was used in control design. In this model, T_m is motor torque, F_d is the driving force at the contact path between tire and road, ω is the rotational velocity of the wheel, r is the wheel radius, and I_ω is the wheel inertia. In this paper, we consider the case of vehicle acceleration only.

Using the model in Fig. 4, the following dynamic equation was derived (in case of acceleration).

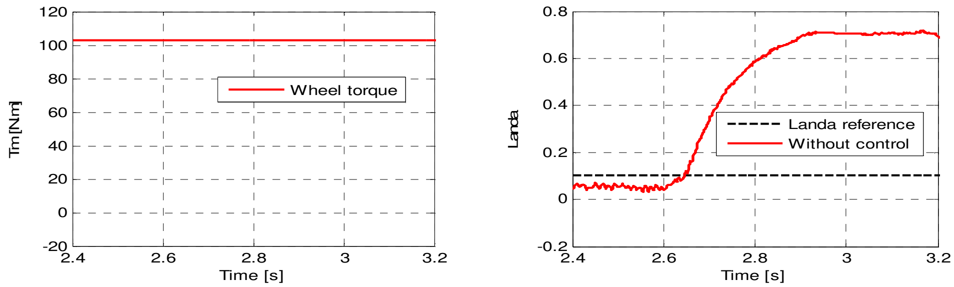
$$\dot{\lambda} = -\frac{\dot{v}_x}{v_x}\lambda + \frac{v_x}{I_\omega r \omega^2} T_m - \frac{\dot{v}_x}{v_x} - \frac{v_x}{I_\omega \omega^2} F_d \tag{4}$$

By proposing the sliding surface as (5) and reaching law as (6), sliding model control law was obtained as (7) for calculating the traction control torque. The stability of the control system was confirmed by verifying the Lyapunov function $V = \frac{1}{2}S^2$. In (7), driving force was observed through the motor torque command and wheel rotational velocity [13]. Slip ratio is calculated from wheel velocity and the estimated longitudinal velocity.

$$S = \left(\lambda - \lambda^*\right) \tag{5}$$

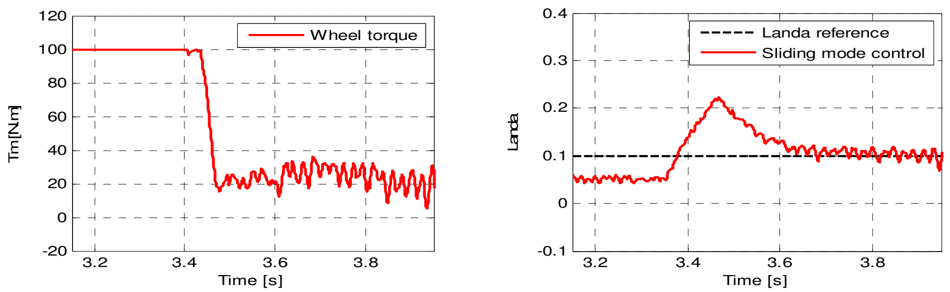
$$\dot{S} = -LS - Qsat(S) \tag{6}$$

$$T_{slide} = \frac{I_\omega r \omega^2}{\hat{v}_x}\left[\frac{\dot{\hat{v}}_x}{\hat{v}_x}\left(1-\hat{\lambda}\right) + \dot{\lambda}^* + \frac{\hat{v}_x}{I_\omega \omega^2}\hat{F}_d - LS - Qsat(S)\right] \tag{7}$$



(a) **(b)**

Figure 8. Longitudinal motion on slippery road-without control:
(a) Motor torque. (b) Wheel slip ratio.



(a) **(b)**

Figure 9. Longitudinal motion on slippery road-with control:
(a) Motor torque. (b) Wheel slip ratio.

The results of traction control on slippery road are demonstrated as follows. In case of without-control, the motor torque is kept constant at maximum value (Fig. 8 (a)). As a result, the slip ratio increases considerably on the slippery road (Fig. 8 (b)). Fig. 9 (a) and (b) show that when the proposed sliding mode control is applied, motor torque is reduced, hence, the wheel slip ratio follows the reference value of 0.1.

6. ROBUST ATTITUDE CONTROL USING DISTURBANCE OBSERVER

In order to guide the EV to follow the desired path, guidance layer compares the estimated positions with the reference values to generate the following commands: yaw angle, sideslip angle, and velocity. Thus, yaw angle control is a basic task of autonomous vehicle control system.

Yaw angle control can be realized based on front steering angle control using a PD or PID feedback controller [14], [15]. However, the vehicle might be interfered by strong disturbances like lateral wind force. Moreover, the cornering stiffness is not a constant due to the change of road friction coefficient. Therefore, robustness is a critical issue in yaw angle control design.

The transfer function from front steering angle to yaw angle is obtained as follows:

$$P_{(\delta_f \to \psi)}(s) = \frac{\psi(s)}{\delta_f(s)} = \frac{b_{21}s + \left(a_{21}b_{11} - a_{11}b_{21}\right)}{s^3 - \left(a_{11} + a_{22}\right)s^2 + \left(a_{11}a_{22} - a_{12}a_{21}\right)s} \tag{8}$$

Disturbance observer has been widely applied as a robust motion control method [7], [8], [16]. According to this method, the feedback loops includes a model of the dynamic of the exogenous reference and disturbance signal, called nominal internal model. By carefully designing the nominal model and Q-filter, the perfect asymptotic tracking and disturbance compensation are achieved. In this paper, the nominal internal model is proposed as follows:

$$P_{(\delta_f \to \psi)n}(s) = \frac{u_x}{(l_f + l_r)s} = \frac{k_n}{s} \tag{9}$$

The comparison of open-loop model (8) and nominal model (9) is illustrated in Fig. 10. The robust stability condition of inner-loop with disturbance observer is:

$$\left|Q(j\omega)\right| < \frac{1}{\left|\Delta(j\omega)\right|} \tag{10}$$

Where $\Delta(s)$ is the boundary function representing model uncertainties. Q-filter can be selected as first-order low-pass-filter. Fig. 11 shows the design of Q-filter that satisfies the robust stability condition (10). The yaw angle control system is demonstrated in Fig. 12.

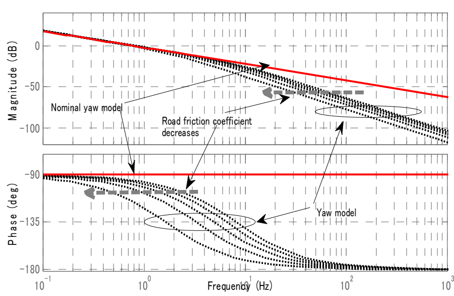


Fig. 10. Nominal and parameter variation mode (at 25 kph).

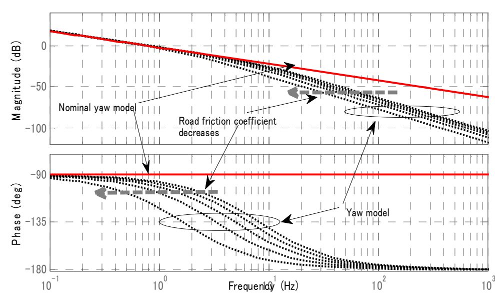


Fig. 11. Q-Filter design to satisfy robust stability condition (at 25 kph).

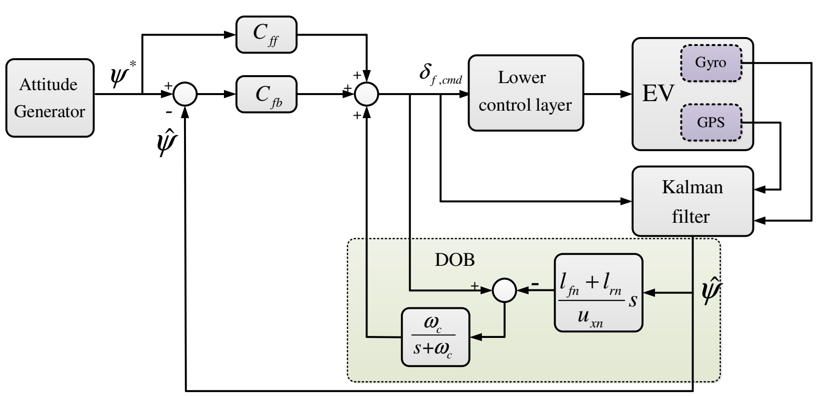
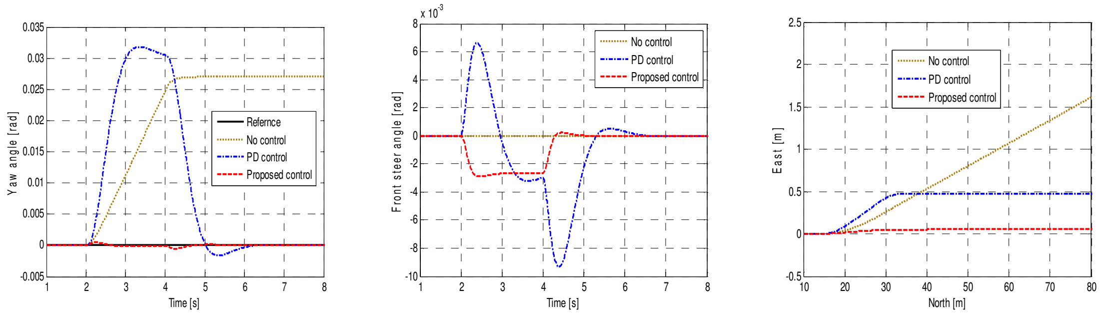


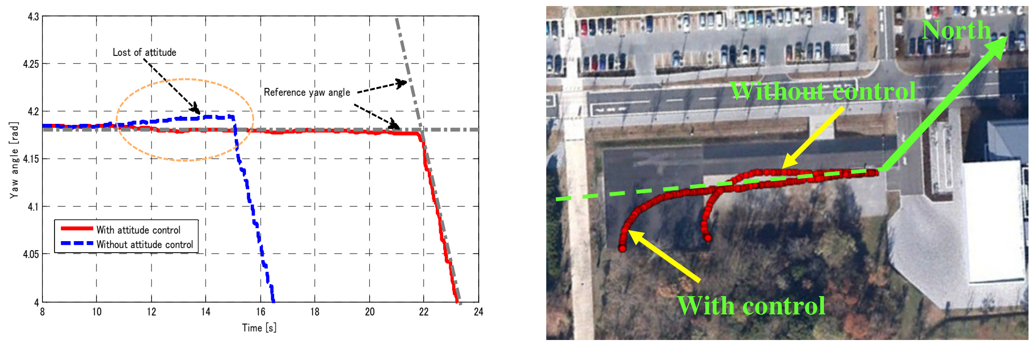
Fig. 12. Attitude control system of EV.



(a) **(b)** **(c)**

Fig. 13. Simulation results of attitude control

(a) Yaw angle. (b) Front steering angle. (c) Vehicle trajectory



(a) **(b)**

Fig. 14. Experimental results of attitude control

(a) Yaw angle. (b) Vehicle trajectory

In the proposed attitude control system, yaw angle is estimated by Kalman filter using GPS. The feed forward controller is designed by inversing the nominal model. The feedback controller is designed as PI controller using pole placement method.

In simulation, vehicle velocity is 25 kph and the vehicle is desired to keep the constant yaw angle which is equal zero. Strong lateral wind force attacks the vehicle as external disturbances. The conventional attitude control method with only feedback controller (PD) is performed for comparison. The PD controller is designed by pole placement using the yaw model (8). Model uncertainties of are introduced to evaluate the robustness issue. The cornering stiffness for feedback control design are $C_{fn} = C_{rn} = 7{,}000$ (N/rad) while the vehicle model is established with $C_f = C_r = 5000$ (N/rad).

Fig. 13 (a) illustrates the response of vehicle yaw angle according to different control methods. Fig. 13 (b) performs the front steering angle which is the control input of attitude control system. Fig. 13 (c) expresses the trajectories of vehicle motion. In case of without control, the front steering angle is always zero, and the vehicle cannot keep the desired attitude under the influence of lateral wind force. When PD controller is applied, it takes a long time for vehicle to recover the desired attitude. Thanks to the proposed control method, disturbance is suppressed and disturbances are compensated. Hence, vehicle can quickly recover the desired attitude. The lateral displacement is also considerably reduced in comparison with that of PD control method.

Autonomous driving control test is conducted to evaluate the proposed control system. In case of without control, steering angle command is pre-calculated before conducting the test. However, the vehicle cannot follow the desired yaw angle. When applying the proposed attitude control, yaw angle tracking is achieved. Responses of yaw angle and vehicle trajectories are showed in Fig. 14 (a) and (b), respectively.

7. CONCLUSIONS

This paper presents an integrated framework of autonomous EV with motion control based on the integration of GPS and on-board dynamics sensor. Accurate state estimation is achieved using Kalman filter considering the time delay of GPS measurement, the inter-sample measurement residual prediction to overcome the low update rate of GPS receiver, and the disturbance/sensor bias estimation. Based on the state estimator, various local controls are designed, such as wheel slip ratio control, lateral stability control, and yaw angle control. Each local control is designed based on robust control theory. Several recent experiment results are discussed in this paper. The results show that GPS can be utilized to improve the safety and stability of transportation using electric vehicles. Future works will focus on autonomous guidance algorithms and other sensors, such as camera and lidar, will be utilized.

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