Estimation and Control of Lateral Displacement of Electric Vehicle Using WPT Information

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***Abstract*—This work proposes a method to estimate lateral displacement of an electric vehicle from wireless power transfer information and vehicles motion measurement through the Unscented Kalman filter. By using the estimated lateral displacement as a feedback variable, the trajectory of vehicle is controlled to the area of high performance transmission. The proposed method is validated by simulation and experiment.**

I. INTRODUCTION

Electric vehicles (EVs) provide the more preferable environmental benefits compared to combustion engine cars. Several automobile manufacturers bring out the electric vehicles into a market. However, electric vehicles are not so attractive to ordinary consumers due to the problems of energy storage. Firstly, the electric energy storage has low energy density. An electric vehicle could operate for a shorter distance with the weight of batteries same as the weight of gas in a combustion engine car. Secondly, batteries need a long charging time. Thirdly, batteries have limited lifetime. They have to be changed in every 2-5 years. Finally, the battery price is expensive. As a result, people still prefer purchasing combustion engine car.

The above problems could be solved if the wireless dynamic charging is applied for practical usage as the electric vehicles could be empowered while running on the road with embedded wireless power transmitter. The wireless power transfer (WPT) technology via coupled magnetic resonance; which has high potential to apply with EVs application, was introduced in 2007[1]. The efficiency over 90 % is reached in stationary charging; however, the misalignment of transmitter coil and receiver coil causes low coupling coefficient. As a result, low transmission efficiency is obtained. Several methods were proposed to improve transmission efficiency, for example, impedance matching[2] and load optimization[5]. However, high coupling coefficient is still required for these methods. Therefore, the vehicle trajectory should be controlled to pass the high coupling area.

Several sensors are used in vehicle control such as GPS, computer vision and laser. However, these sensors have some limitations and could not directly detect the position of power transmitter. There are some papers proposing method for estimating position using WPT information. The paper [3] measured the reflection coefficient vector from every transmitter in the system through vector network analyzer (VNA) and the position is estimated by mapping that vector in the database. However, this configuration is not suitable for EV application because of the price of VNA. Another paper[4] proposed a control method to stop a vehicle at the maximum power transfered point in one dimension according voltage and voltage derivative in secondary side. However, the exact position is not estimated and the position in two dimension should be considered in actual application. This paper proposes method for estimating lateral displacement of the electric vehicle with respect to the alignment of transmitters by using information from WPT receiver side and onboard motion sensors. The estimated result is applied for a feedback control of lateral displacement to achieve high coupling area.

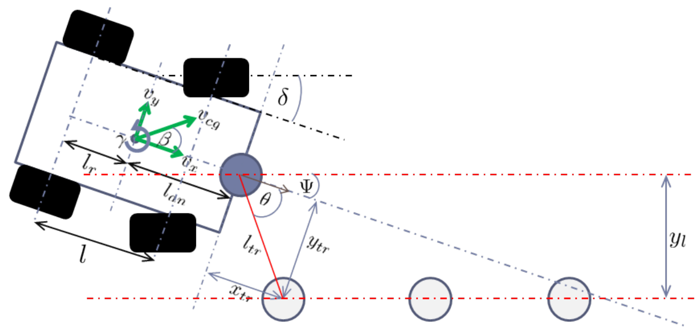

Fig. 1. Schematic of electric vehicle with WPT receiver

In this paper, the model related to this work is derived in Section II. The estimation applies Unscented Kalman filter (UKF) and is validated by experiment in Section III. The feedback control of lateral displacement employs the estimated lateral displacement is described in Section IV.

II. MODEL OF VEHICLE WITH WPT RECEIVER

The schematic of an electric vehicle with WPT receiver is illustrated in Fig. 1. The parameters l_f and l_r is distance from the center of gravity to front wheel axis and rear wheel axis respectively. The vehicle motions considered in this paper is including longitudinal velocity v_x, lateral velocity v_y and yaw

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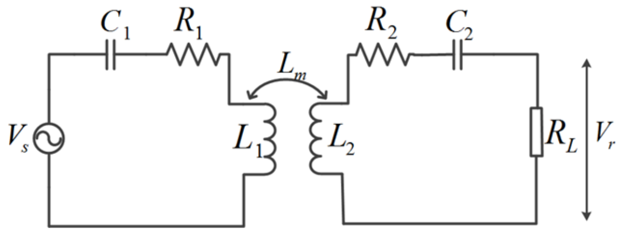


Fig. 2. WPT equivalent circuit

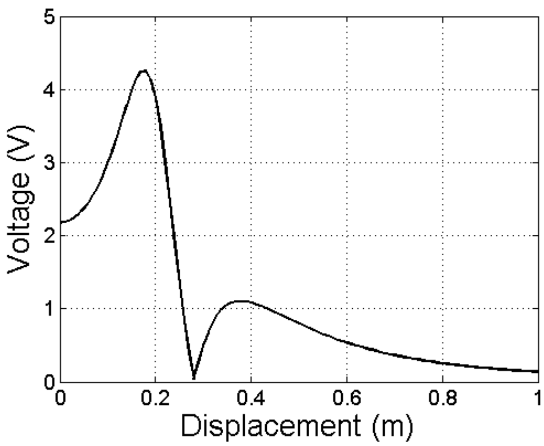


Fig. 3. Voltage-displacement characteristics

rate γ. The motion in vertical gap from vibration, pitch and roll rotation is neglect. The WPT receiver is mounted in front of a vehicle with a length l_{an} from the vehicle's center of gravity.

Two coordinate systems are considered in this work. The first system is relative position of a receiver with respect to single transmitter. The measurement from WPT system is directly related to this system. The second system is lateral displacement with respect to the alignment of transmitters. The goal of estimation and control is concerned with this system.

A. Differential Equation of Relative Position

This model describes the relative position of one transmitter with respect to a receiver on vehicle. Referring to Fig. 1, relative position is defined by displacement from the receiver to the transmitter l_{tr} and orientation θ where the differential equation is expressed as:

$$\dot{l}_{tr} = (v_y + \gamma l_{an}) \sin\theta - v_x \cos\theta \tag{1}$$

$$\dot{\theta} = \frac{(v_y + \gamma l_{an}) \cos\theta + v_x \sin\theta}{l_{tr}} + \gamma \tag{2}$$

B. Differential Equation of Lateral Displacement

This model illustrates the lateral displacement y_l and heading angle Ψ of the receiver with respect to the alignment of transmitters. The motion in this system is expressed as:

$$\dot{y}_l = (v_y + \gamma l_{an}) \cos(\Psi) - v_x \sin(\Psi) \tag{3}$$

$$\dot{\Psi} = -\gamma \tag{4}$$

C. Transfer Function

From kinematic model, yaw rate and side slip is expressed as:

$$\gamma = \frac{V}{l} \cos(\beta) \tan(\delta) \tag{5}$$

$$\beta = \tan^{-1}\left(\frac{l_r}{l} \tan(\delta)\right) \tag{6}$$

where δ is front steer angle.

Assuming that the steering angle and side slip angle is small, yaw rate and side slip angle could be approximately expressed as:

$$\gamma \approx \frac{v_x}{l} \delta \tag{7}$$

$$\beta \approx \frac{l_r}{l} \delta \tag{8}$$

Substituting these approximations to equation 3 and 4, the state space equation is expressed as:

$$\begin{bmatrix} \dot{y}_l \\ \dot{\Psi} \end{bmatrix} = \begin{bmatrix} 0 & -v_x \\ 0 & 0 \end{bmatrix} \begin{bmatrix} y_l \\ \Psi \end{bmatrix} + \begin{bmatrix} \frac{v_x}{l}(l_r + l_{an}) \\ -\frac{v_x}{l} \end{bmatrix} \delta \tag{9}$$

The transfer function from front steering angle to lateral displacement is derived as:

$$\frac{Y_l(s)}{\delta(s)} = \frac{s v_x (l_{an} + l_r) + v_x^2}{l s^2} \tag{10}$$

This transfer function will be used in controller design.

D. WPT Equivalent Circuit

The WPT equivalent circuit is illustrated in Fig. 2. Under the assumption of perfect resonance, the voltage across a constant load on the receiver side V_r is expressed as [5]

$$V_r = \left| \frac{\omega_0 L_m R_L}{R_1 R_L + R_1 R_2 + (\omega_0 L_m)^2} \right| V_s \tag{11}$$

where
V_s voltage source;
R_L resistive load;
R_1 resistance in transmitter coil,;
R_2 resistance in receiver coil;
L_m mutual inductance.

As the WPT parameters V_s, R_L, R_1 and R_2 are constant, the voltage across load in receiver side V_r relies only on mutual inductance between a transmitter coil and a receiver coil. Additionally, the mutual inductance between spiral circular coils with definite dimension and vertical gap would depend only on displacement between receiver coil and transmitter coil l_{tr}. The paper [6] proposes a method to calculate mutual inductance between spiral coils.

In the experiment, the inner radius and outer radius of coils are 5.1 cm 15.0 cm respectively. The vertical gap is 15 cm.

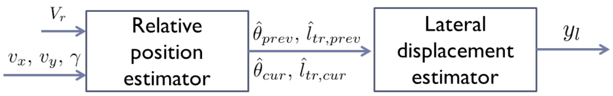


Fig. 4. Estimation process block diagram

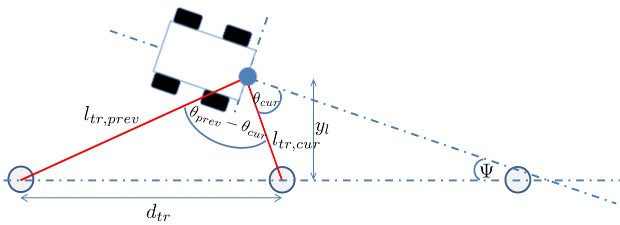


Fig. 5. Vehicle with wireless power transmitter alignment

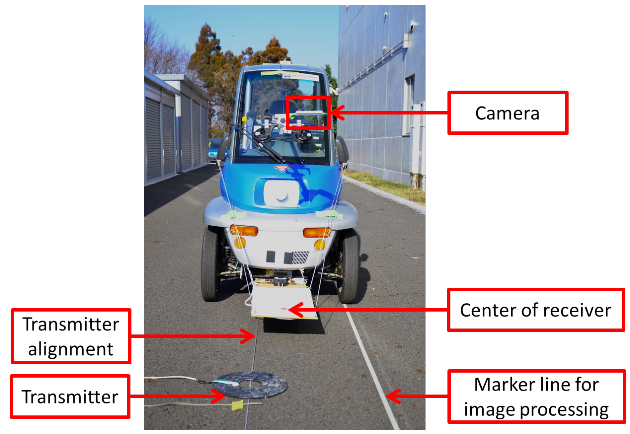


Fig. 6. Experiment setup

The WPT system parameters are $V_s = 3.54$ V, $R_1 = 1.62$ Ω, $R_2 = 0.74$ Ω and $R_l = 10.1$ Ω. As a result, the voltage across load V_r is a only function of displacement l_{tr} as shown in Fig. 3. The voltage is drastically dropped as the displacement l_{tr} increases over 15 cm because the high coupling between two coils could be maintained up to this range. This voltage-displacement characteristic will be directly used in measurement prediction in UKF on the next section.

III. Lateral Displacement Estimation

The block diagram of lateral displacement estimation process is shown in Fig. 4. The relative position is estimated by utilizing vehicle motion and measurement from receiver side through the Unscented Kalman filter. Not only the relative position to current transmitter is estimated, but the relative position to the previous transmitter is also simultaneously predicted. The lateral displacement is calculated from these data.

The Kalman filter (KF) provides optimal estimation according to process model, measurement model, input, measurement and initial state[7]. Because the motion equation of the vehicle with receiver and the measurement in WPT receiver are nonlinear. Although there are two well known algorithm for estimating in nonlinear system; Extended Kalman filter (EKF) and Unscented Kalman filter (UKF), the UKF could provide more reliable estimation especially in case of the higher initial state error and higher speed. The UKF was proposed to estimate states in nonlinear system using accurate statistic approximation based on sigma points called the unscented transformation (UT)[8] while the EKF computes the statistics through first-order linearization. This is a fundamental reason on why the UKF provides better estimation result.

A. Estimation of Relative Position to Single Transmitter

The estimation of relative position applies UKF algorithm. The state vector is relative position defined as $x = [l_{tr}\ \theta]^T$. The measurement is voltage across constant load in secondary side defined as $y = V_r$. The input is vehicle motion defined as $u = [v_x\ v_y\ \gamma]^T$. By discretizing Eq. (1) and (2) with forward Euler method, the process equation, used in state prediction, is expressed as

$$l_{tr,k+1} = l_{tr,k} + T_s\left((v_{y,k} + \gamma l_{an})\sin\theta_k - v_{x,k}\cos\theta_k\right) \quad (12)$$

$$\theta_{k+1} = \theta_k + T_s\left(\frac{(v_{y,k} + \gamma_k l_{an})\cos\theta_k + v_{x,k}\sin\theta_k}{l_{tr,k}} + \gamma_k\right) \quad (13)$$

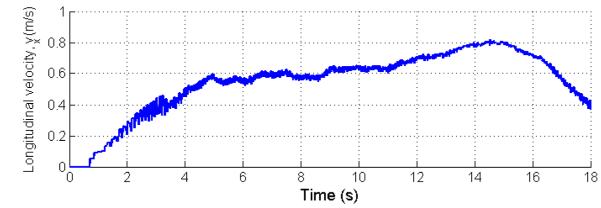
The measurement equation, employed in measurement prediction, is directly applied a lookup table from voltage-displacement characteristics in Fig. 3.

The estimation would be held over until the receiver voltage higher than threshold voltage $V_{th} = 1.7$ V is measured. Once the threshold voltage is received, the estimator directly applies UKF algorithm. When the UKF is initiated, the initial state must be known. The initial displacement $l_{tr,0} = 0.25$ derived from voltage-displacement characteristics. Using only one receiver, there is limited capability to detect the transmitter side. Therefore, it is necessary to make the assumption that the transmitter is on the right side of the vehicle. In another word, the initial orientation θ_0 is set to positive real value. At this step, the estimated relative position would converge to the actual value. Subsequently, if the voltage is under the threshold, the estimation would rely only on prediction according to Eq.(12) and (13). At this period, the receiver is leaving the current transmitter and going forward to the next transmitter. The UKF would be applied again when the voltage information of next transmitter is over the threshold.

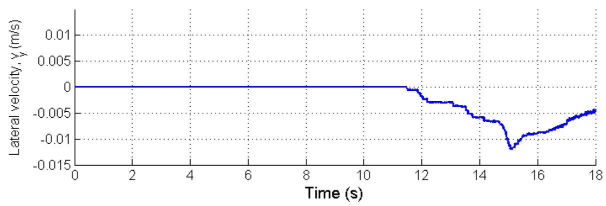
B. Calculation of Lateral Displacement to Transmitter Alignment

The lateral displacement is impossible to be obtained from relative position of only one transmitter. According to Fig. 5, if the relative positions of two transmitters are known, the lateral displacement can be computed by

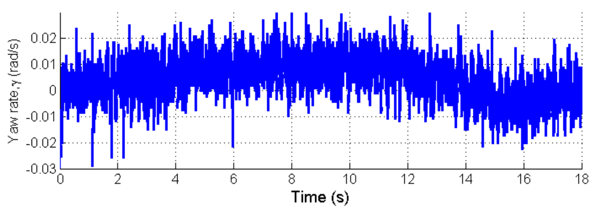
$$y_l = \frac{l_{tr,prev}l_{tr,cur}\sin(\theta_{prev} - \theta_{cur})}{d_{tr}} \quad (14)$$



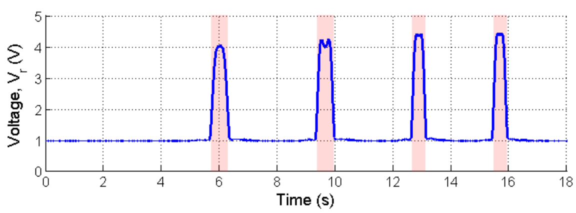
(a) Longitudinal velocity, v_x



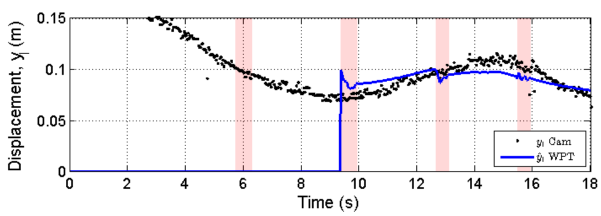
(b) Lateral velocity, v_y



(c) Yaw rate, γ



(d) Receiver voltage, V_r



(e) Lateral displacement, y_l

Fig. 7. Estimation results

where

$(l_{tr,prev}, \theta_{prev})$ relative position to previous transmitter;

$(l_{tr,cur}, \theta_{cur})$ relative position to current transmitter;

d_{tr} interval between each transmitter.

The estimator must continue predicting the relative position to the previous reference transmitter although the measurement from next transmitter is available and the position to the next transmitter is estimated. By this way, the relative position to two transmitter is obtained by calculating the actual lateral displacement according to (14).

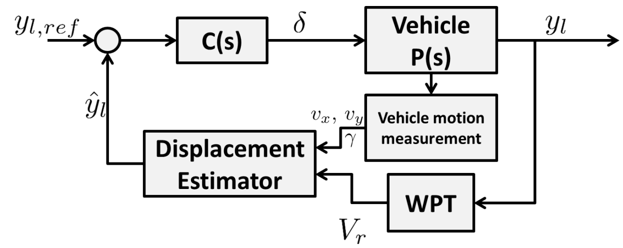


Fig. 8. Control system block diagram

C. Experiment Setup

The WPT receiver is mounted in front of an electric vehicle COMS manufactured by Toyota Auto Body Co., Ltd. as shown in Fig. 6. The data from motion sensors and WPT receiver are collected and processed in real time by an onboard RT-linux computer. The interval between each transmitter is 2 m. The camera is also mounted to record video which will be processed for lateral displacement to compare with the estimation result.

D. Experiment

The vehicle moves along the transmitters with the vehicle motion in Fig. 7a, 7a and 7c. The measured voltage in this experiment is shown in Fig. 7d. The voltage over 1.7 V, shaded in red, is employed in update process in UKF. The estimation of lateral displacement is shown in the blue line in Fig. 7e while the black line is the lateral displacement processed from computer vision. The estimation starts when the information from the second transmitter is received. The estimation result is consistent with the lateral displacement computed by computer vision. There is error in estimation caused by the imperfect experiment setup. As mentioned at the beginning of this section, the correctness of estimation result depends on the accuracy of measurement model, input, process model and measurement. The resistance of each transmitter coil is not exactly the same causing a small difference in voltage-displacement characteristics. The vehicle motion measurement is also the cause of error. Also, the lateral displacement is calculated from the predicted relative position from the previous transmitter. The error could also occurs in this process.

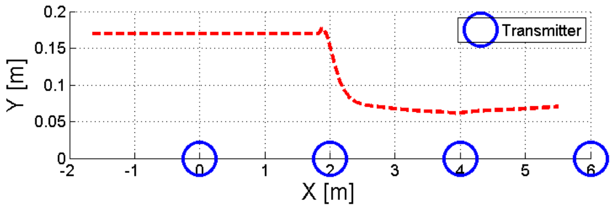
IV. Control of Lateral Displacement

The feedback controller applies the estimated lateral displacement discussed in the previous section to calculate a steering input to control the vehicle. The block diagram of the control system is shown in Fig. 8.

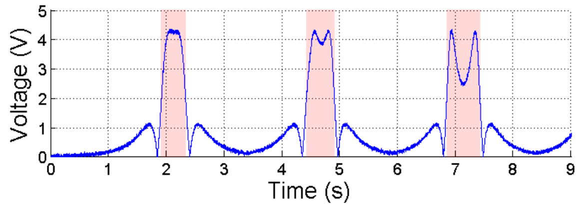
A. Controller Design

The PD controller is selected as a feedback controller in order that two poles of the close loop could be arbitrarily placed.

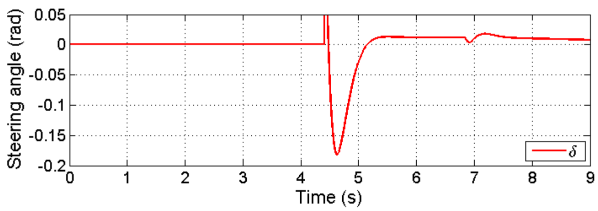
The controller is designed based on the nominal model in equation which is corresponding to these parameters: $V_x = 0.8$ m/s, $l = 1.2$ m, $l_r = 0.4$ m.



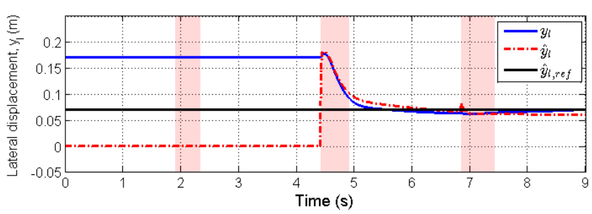
(a) Trajectory



(b) Receiver voltage, V_r

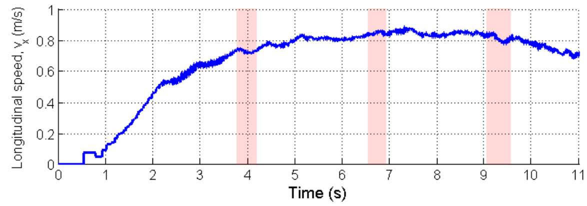


(c) Steering angle, δ

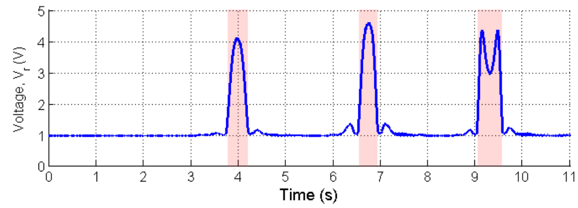


(d) Lateral displacement, y_l

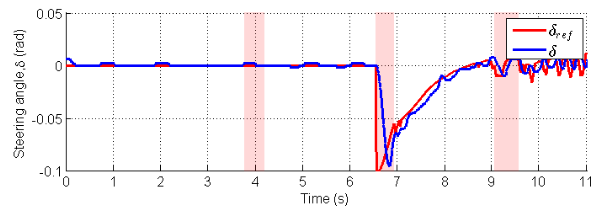
Fig. 9. Control simulation



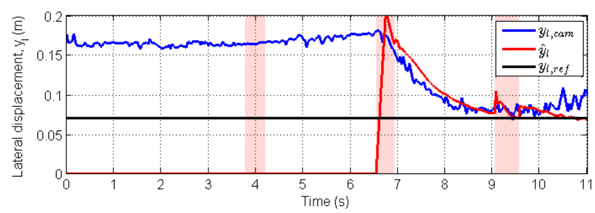
(a) Longitudinal velocity, v_x



(b) Receiver voltage, V_r



(c) Steering angle, δ



(d) Lateral displacement, y_l

Fig. 10. Control experiment

$$\frac{Y_l(s)}{\delta(s)} = \frac{1.4667s + 0.5333}{s^2} \tag{15}$$

The transfer function of the PD controller is

$$C_{PD}(s) = K_P + K_D s \tag{16}$$

If poles are placed at $s = p_1, p_2$, the gain is calculated as $K_P = \frac{(a+1)p_1 p_2}{b}$ and $K_D = -\frac{(a+1)(p_1 + p_2 + p_1 p_2)}{a}$ where $a = \frac{v_x(l_a n + l_r)}{l}$ and $b = \frac{v_x^2}{l}$.

The main criteria of control design is small maximum overshoot due to the limitation of the estimator while the acceptable settling time is around 4 seconds.

B. Simulation

In simulation, the vehicle moves with a constant lateral velocity at 0.8 m/s. The initial lateral displacement is 0.17 m while the reference lateral displacement is 0.07 m. The gain K_p and K_d is 0.87 and 1.37 respectively in order to place the poles at $s = -0.25, -0.75$. The controller would start as soon as the estimated lateral displacement is available. The simulation result is shown in Fig. 9. The vehicle trajectory converges to the reference lateral displacement as show in Fig. 9a. The steering angle is shown in Fig. 9c. The controller is started when reaching the second transmitter. The actual lateral displacement and the estimated lateral displacement, used for feedback control, is shown in Fig. 9d. The vehicle could achieve reference lateral displacement before reaching the third transmitter.

C. Experiment

The experiment result is shown in Fig. 10. The controller starts when the lateral displacement estimator begins. The longitudinal velocity is shown in Fig. 10a which almost the same as speed used for controller design. The voltage is shown in Fig. 10b. The steer command is shown in Fig. 10c making an effort to control the vehicle displacement to the reference. The red line is the designed steering angle while the blue line is the actual steering angle. The lateral displacement is shown in Fig. 10d. The black line is the reference lateral displacement which is 0.07 m. The blue line is the lateral displacement processed from vision sensor while the red line is the estimated lateral displacement. The result show that it could almost achieved the reference lateral displacement before reaching the third transmitter. Although there is error in the estimation with the same reason mentioned in the previous section, the controller is still able to control the vehicle.

V. Conclusion

The lateral displacement estimation is proposed based on UKF and verified by experiment. The estimated result is applied to control the vehicle. The error occurs mainly from the inaccurate measurement model because of the imperfect in experiment setup. However, goal of controlling the vehicle to high coupling area is achieved. Although this experiment is performed at low speed due to safety reason and limited experiment setup, it proves the concept of using WPT information for control the vehicle.

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