Sensorless Automatic Stop Control of Electric Vehicle in Semi-dynamic Wireless Power Transfer System with Two Transmitter Coils

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***Abstract*—Semi-dynamic wireless power transfer (SDWPT) system is one of the solutions to short driving distance in electric vehicle (EV). This system provides electric power to EVs on the point of stopping. A scheme of sensorless positioning system in SDWPT system via magnetic resonance coupling is proposed in this paper. High transmission efficiency and short vehicular gap position are selected as the final stop position which lead to energy conservation and traffic jam problem reduction. These proposed methods also show more practicality of positioning system for SDWPT system by using command value prediction (CVP) and reinforcement learning algorithm (RLA). Performance of these two proposed method is evaluated by simulations and experiments. The results pointed out that these two proposed methods are able to stop the vehicle at the high transmission efficiency position without any visual sensor.**

***Index Terms*—Sensorless automatic stop, Wireless power transfer, Semi-dynamic wireless power transfer, Electric vehicle, Reinforcement learning**

I. Introduction

Electric Vehicle (EV) is well known as the new choice for vehicles in the future as it reduces CO_2 emission. However, the common power source in EV, Li-ion battery is not able to provide energy as much as gasoline does. Thus, EVs normally occupy short range driving comparing to gasoline cars.

Some of advanced studies [1] applied WPT system to electric vehicle. Static wireless power transfer system was implemented as the first stage of WPT system in EVs. Still, static wireless power transfer system could not solve the EV's short driving range problem.

Semi-dynamic wireless power transfer (SDWPT) system is one of the applications of WPT system. As shown in Fig. 1, SDWPT system performs power transmission while EV decelerates and stop its motion at particular position [2]. For instance, if transmission equipment is installed beneath the road where is adjacent to the intersection with a traffic light, EVs are able to acquire electric power while they are waiting at the traffic light. This system is capable of providing sufficient electric power to extend the driving range of EVs [3].

Former Research [5] shows the stop position estimation method for SDWPT system by current change during transmission. Still, this proposed method is unable to be used in case of multiple transmitter coils. Moreover, stop position error increases in case EVs' moving direction have angular

Fig. 1. Semi-dynamic wireless charging system in EVs.

misalignment with transmitter coils. Moreover, the faster EVs move, the more stop position error occurs.

This paper proposes the sensorless automatic stop control in SDWPT system by using CVP and RLA. These two proposed methods are not only applicable to linear motion of EVs at practical velocity in SDWPT system (e.g. $5\,\mathrm{km/h}$), but also yield the higher transmission efficiency of the system. Position which has high transmission efficiency and short vehicular gap is chosen to be the stop position aiming for energy conservation and traffic jam reduction.

In this paper, application of CVP and RLA in sensorless automatic stop control algorithm is proposed. Then, the validity and the effectiveness of proposed methods are presented by simulations on automatic stop control and bench test experiment.

II. Problem Setting

A. Automatic Stop Scene

Our laboratory developed second generation wireless in-wheel motor with dynamic wireless power transfer system [4]. In this paper, EV in SDWPT system is based on this vehicle model as shown in Fig. 3.

In previous research [5], sensorless stop position estimation algorithm by received current gradient was proposed in case of transmission for a single transmitter coil. There was estimated stop position error due to the asymmetric property of transmitter coil caused by the angular misalignment when EV

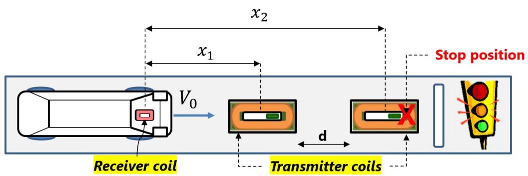


Fig. 2. Problem setting (top view).

approaches the transmitter coil. Since this conventional method uses the information from the first half of the transmitter coil to predict the information in later half of the transmitter coil, if the transmitter coil has no symmetric property, the proposed method might cause the stop position error.

For these reasons, stop position estimation by the information from only one transmitter coil might be insufficient to acquire the accurate stop position. Thus, if more transmitter coils are installed, EV will be able to obtain more information from transmitter coils and improve the performance of automatic stop control.

This section explains the problem setting considered in proposed methods of automatic stop control in SDWPT system using learning algorithm including CVP and RLA. As shown in Fig. 2, two transmitter coils are installed beneath the road next to the intersection area with the distance d from each other. Transmission occurs after EV is detected by the current search pulse [6]. EV obtains the electric power (WPT information) and use it for learning algorithm simultaneously before performing automatic stop control to stop at the specified position at second transmitter coil. By these proposed method, EV is able to get the information from the whole transmitter coil compared to the conventional method which the information was obtained from only a half of the transmitter coil [5].

In automatic stop control, vehicle will decelerate to stop at particular position. Each stop position provides different transmission power and efficiency due to the change of mutual inductance between coils [7]. In this paper, high transmission efficiency and short vehicular gap are selected as the conditions of stop position. Only x-axis motion is considered. Here, x_1 and x_2 are defined as the horizontal misalignment between the center of receiver coil and the center of each transmitter coil as shown in Fig.2. Receiver coil is attached to the EV at origin position (x = 0).

B. Wireless Power Transfer System

Fig. 4 shows the equivalent circuit of WPT circuit used in this SDWPT system. V_{11} and V_{12} represent the voltage source of first and second transmitter coil respectively. Circuit parameters R_1, L_1, C_1, R_2, L_2 and C_2 are resistance, inductance, capacitance in primary and secondary side respectively.

Constant voltage source V_{2dc} is used as a load on secondary side in order to model battery charging in EVs. M is the mutual inductance between transmitter coil and receiver coil which varies with the relative position of these coils. In order to maximize the transmission efficiency, both coils ought

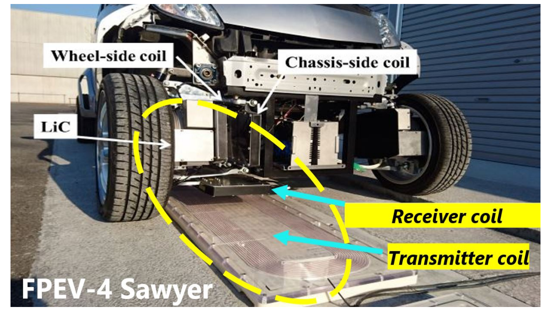


Fig. 3. Experiment transmitter coil and receiver coil.

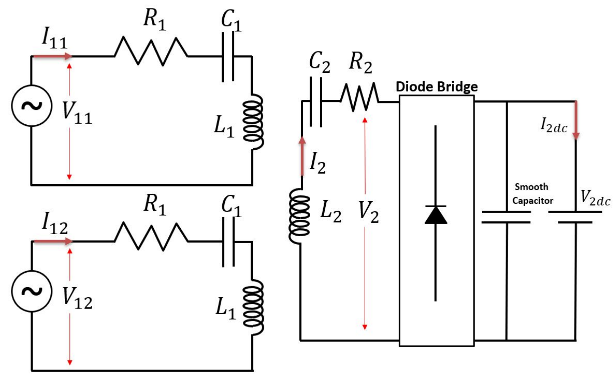


Fig. 4. Wireless Power Transfer (WPT) equivalent circuit.

to have the same resonance frequency ω_0 [8]. Resonance frequency condition is given in (1) [9].

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_1 C_2}} \tag{1}$$

According to the circuit equation from WPT circuit in Fig. 4, I_{11}, I_{12} and I_2 are given as the root mean square value of alternating current (AC) in first, second transmitter coil and receiver coil respectively, which can be solved as shown in the following equation (2).

$$\begin{aligned} I_{11} = I_{12} &= \frac{\omega_0 M V_2 + R_2 V_1}{R_1 R_2 + \omega_0^2 M^2} \\ I_2 &= \frac{\omega_0 M V_1 - R_1 V_2}{R_1 R_2 + \omega_0^2 M^2} \end{aligned} \tag{2}$$

From the current values in equation (2), transmitted power in first, second transmitter coil are defined as P_{11}, P_{12} and received power at the secondary side is given as P_2 which can be calculated by equation (3).

$$\begin{aligned} P_{11} &= V_{11} I_{11} \\ P_{12} &= V_{12} I_{12} \\ P_2 &= V_2 I_2 \end{aligned} \tag{3}$$

Finally, transmission efficiency η_1, η_2 are able to be expressed in the following equation (4) [10].

$$\begin{aligned} \eta_1 &= \frac{P_2}{P_{11}} \times 100[\%] \\ \eta_2 &= \frac{P_2}{P_{12}} \times 100[\%] \end{aligned} \tag{4}$$

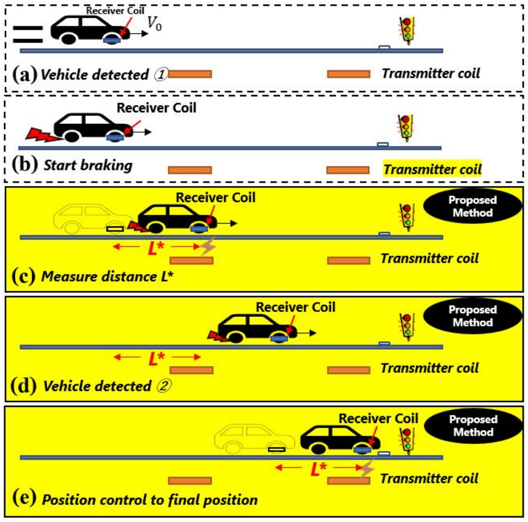


Fig. 5. Command value prediction in automatic stop control.

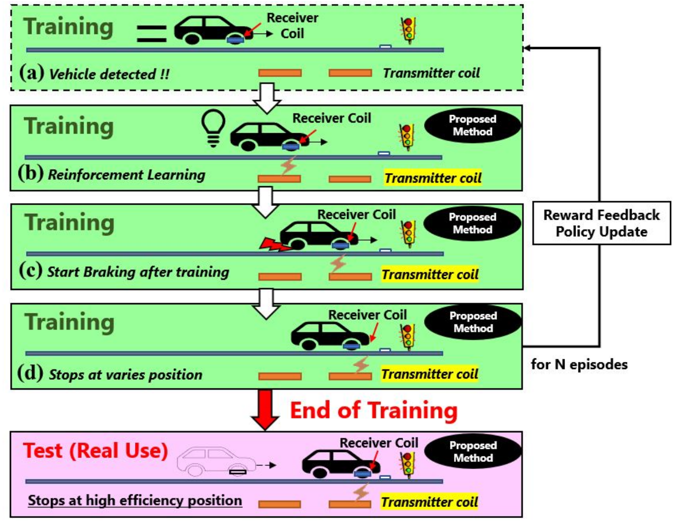


Fig. 6. Reinforcement learning algorithm in automatic stop control.

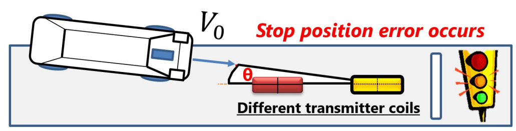


Fig. 7. Weakness of command value prediction method.

III. Automatic Stop Control Algorithm

In this paper, two automatic stop control algorithms are proposed, which are command value prediction (CVP) and reinforcement learning algorithm (RLA) respectively. The algorithm of each proposed method is explained in this section. Then, the performance of both proposed methods is evaluated by simulations in next section.

A. Command Value Prediction (CVP)

The automatic stop control algorithm by the command value prediction is shown in Fig. 5.

(a) EV is detected by the voltage search pulse from the transmitter coil [6] when it has approached the first transmitter coil.
(b) EV starts to decelerate itself after it has been detected.
(c) EV starts measuring braking distance L^* right after the vehicle detection until it reaches the maximum transmission efficiency position of the first transmitter coil.
(d) EV has passed through the first transmitter coil and has been detected by the second transmitter coil.
(e) EV uses the measured braking distance L^* as the command value to perform position control and stops at high transmission efficiency position at the second transmitter coil.

In this proposed method, EV measures the appropriate braking distance L^* from the first transmitter coil and use this value to perform automatic stop control. This stop control algorithm is simple to implement but it is based on the condition that both of transmitter coils ought to be identical.

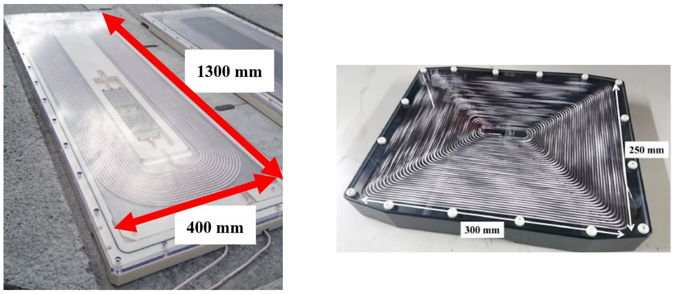
Still, if two transmitter coils do not have the same property, the stop position error might increase in addition to the error from position control system.

B. Reinforcement Learning Algorithm (RLA)

Recently, reinforcement learning for autonomous driving has been applied to many autonomous driving and braking system [11]. Deep reinforcement learning (DRL) has shown the desirable performance for various challenging motion control problems. In real application of this system, vehicle might approach the transmitter coils with angular misalignment (Fig. 7) or each of transmitter coil has different characteristics. In these cases, stop position error might occur in aforementioned command value prediction method since the information from first transmitter coil is referred as the command value in automatic stop control for stopping at second transmitter coil.

Application of RLA to automatic stop control in this paper is shown in Fig. 6. Automatic stop control program is installed into real EV after it has been trained and validated the performance in computer. In this system, agent (EV) performs an action $a \in A_t$ given state $s \in S_t$ under policy π. The agent receives the state s as feedback from the environment (transmitting infrastructure) and obtains the reward R which depends on the agent's taken action a. Possible action that the agent is able to perform is among deceleration, keeping the current velocity and acceleration.

The goal of this proposed automatic stop control is to maximize the expected reward which is subject to the transmission efficiency at the stop position. Each episode of training begins after the agent has passed the first transmitter coil and entering the second transmitter coil. Agent obtains the information from the first transmitter coil and will choose the action by ϵ-greedy algorithm from possible action and get the reward from the



(a) Transmitter coil (b) Receiver coil

Fig. 8. Experiment transmitter coil and receiver coil

TABLE I
WPT CIRCUIT PARAMETERS

Parameter	Transmitter coil	Receiver coil
Resistance [mΩ]	$R_1 = 342.5$	$R_2 = 383.3$
Inductance [μH]	$L_1 = 429.0$	$L_2 = 377.7$

environment [12].

The agent learns from interaction with the environment through training for several times (episodes) and starts to choose the appropriate action to maximize the reward obtained from the environment. Eventually, the agent is able to stop at more accurate position which occupies high reward (high transmission efficiency).

IV. Automatic Stop Control Simulation

A. Simulation Condition

Voltage sources in primary side V_{11}, V_{12} and secondary side V_2 are matched equally since the transmission efficiency increases by setting both V_{11} and V_{12} equal to V_2 [14]. Voltage source is given as $V_{11} = V_{12} = V_2 = 80\,\text{V}$ due to the experiment equipment restriction. The gap length between receiver coil and transmitter coils is defined as 10 cm. WPT circuit parameters in Table I is used as simulation conditions.

According to the problem setting in Fig. 2, transmitter coils shown in Fig. 8(a) are placed at the position x_1 = 2000 mm and x_2 = 4000 mm (d = 500 mm). Receiver coil shown in Fig. 8(b) is driven from the origin point (x = 0) through the traffic light on the right side in Fig. 2 at random velocity $V_0 = 1000 \sim 1300$ mm/s (3.6 $\sim$ 4.7 km/h). These velocity values are chosen considering the assumed possible velocity in SDWPT system (low velocity zone) [2].

Mutual inductance M between a pair of coils at each position is able to be calculated by Neumann formula [13]. The interference of magnetic flux between two transmitter coils is negligible since the distance between two transmitter coils is large enough (d = 500 mm) to ignore this interference effect. Transmission efficiency η_1 and η_2 at each position can be calculated from (2) - (4). Resistance and inductance of primary and secondary side circuit are shown in Table I. Resonance frequency of both coils is given as $f_0 = 85\,\text{kHz}$.

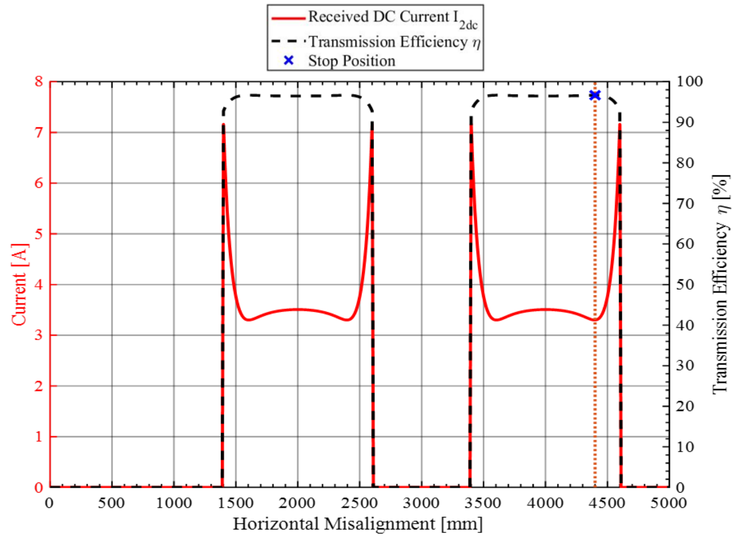


Fig. 9. Simulation result from CVP method (V_1 = 80 V).

B. Simulation Result of Command Value Prediction Method

In spite of initial velocity, command value prediction method in automatic stop control acquires the transmission efficiency and received current value as shown in Fig. 9. From the result in Fig. 9, The simulation result also indicates that if received current decreases, the transmission efficiency increases. Therefore, at final position in this case, transmission efficiency reaches maximum value at horizontal misalignment x = 4400 mm. Here, the braking distance L^* was approximately measured as 1000 mm as shown in Fig. 9.

As mentioned before, this simulation was considered in case of identical two transmitter coils. If there is any bias in each of transmitter coil, the inappropriate braking distance L^* might be used as the command value of position control and eventually cause the stop position error. This problem will be discussed later in next section.

C. Simulation Result of Reinforcement Learning Method

After training process, agent's performance validation is evaluated by testing process and the trained automatic stop control system will be finally installed in real EV for practical use.

According to testing process in Fig. 10 - 11, stop position remains the variance with initial velocity. In some episodes of testing, agent passed through the maximum transmission efficiency position (x = 4400 mm) for 300 mm and stopped at the position which is out of transmission area. This situation gave zero transmission efficiency.

Let us give the success condition as $\eta_2 \geq 90\%$, the testing result pointed out that this RLA proposed method succeeded in automatic stop control by 93.7%. This RLA proposed method sometimes failed in stopping at the desired position because there is random selection in agent's action even after it has been trained. If the number of training episode increases, the number of failure might decreases.

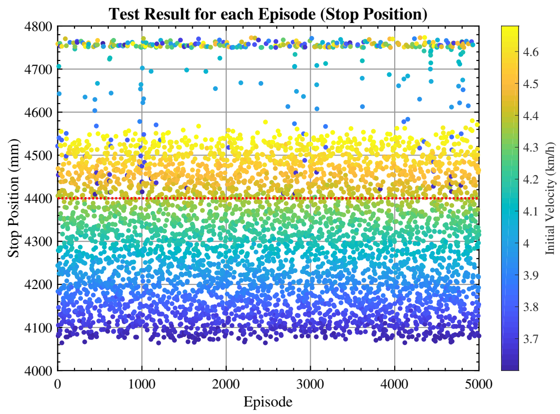


Fig. 10. Testing result (Stop position).

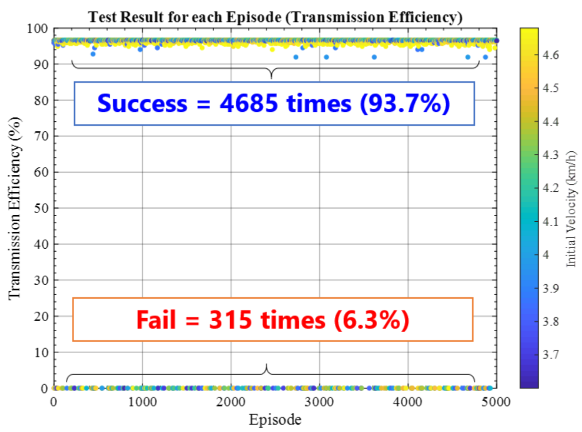


Fig. 11. Testing result (Transmission Efficiency).

V. Experiment on Automatic Stop Control

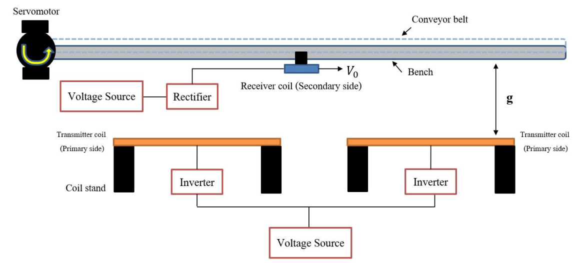
A. Experiment setup

Aforementioned in Section II, the proposed method aims for high efficiency and short vehicular gap positioning in EV without any sensor equipment. Semi-dynamic wireless charging system's experiment setups in this research are explained below.

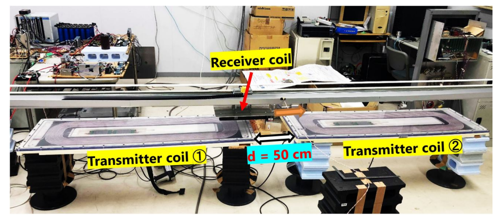
In this paper, experiment on bench model was implemented based on simulation conditions in the previous section which represents the one-dimensional motion of electric vehicle (Fig. 12(a)). The experiment is validated by bench test drive equipment which receiver coil represents the EV as shown in Fig. 12(b).

Receiver coil's velocity is measurable in this experiment. Still, EV's velocity is not measurable in real application. In order to acquire more accurate velocity estimation and precise stop control of EV, slip ratio estimation and regenerative brake control are proposed [15].

The vehicle approaches the first transmitter coil at three different velocities V_0 = 4.7 , 7.1 and 9.4 km/h toward the traffic light located on the right side of the second transmitter coil. The experiment was conducted for 10 times for each



(a) Experiment setup (side view).



(b) Real experiment equipment setup.

Fig. 12. Experiment equipment setup.

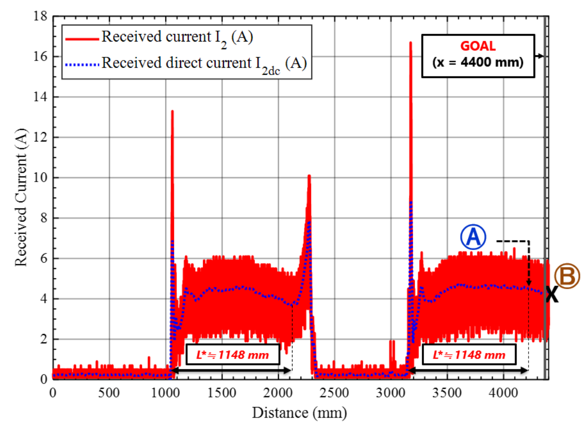


Fig. 13. Received direct current ($V_0 = 9.4$ km/h).

velocity in order to examine the certainty of command value prediction (CVP) method. During wireless power transmission, the receiver coil was positioned at particular stop position by using the information from received direct current I_{2dc} in order to validate the effectiveness of command value prediction method.

B. Experiment result

From one of the ten experiments result at velocity $V_0 = 9.4$ km/h, the received current waveform from bench test drive experiment is shown in Fig. 13. Received current waveform in Fig. 13 shows that each transmitter coil does not have the exactly same property which might be considered as the effect from the measurement noise and interference of magnetic field

TABLE II
STOP POSITION ERROR ANALYSIS

Parameter \ Velocity	4.7 km/h	7.1 km/h	9.4 km/h
Mean (mm)	4313.0	4260.37	4293.52
S.D. (mm)	59.48	42.04	55.27
RMSE (mm)	4313.41	4260.58	4293.88

of two transmitter coil. Still, the measurement result in Fig. 13 is similar to the simulation result in Fig. 9.

In Fig. 13, brake distance command value L^* was predicted as $L^* = 1148$ mm. This predicted value yielded the stop position at $x \approx 4230$ mm (Point A) which has stop position error from the ideal stop position $x = 4400$ mm. In this experiment, stop position feedback control was applied to improve more stop control accuracy by using the slope of the received current as the input of feedback system [5]. This compensation yielded the stop position at $x \approx 4437$ mm (Point B) which has less stop position error.

As mentioned above, command value prediction (CVP) method caused the stop position error when each of transmitter coil has different properties. Therefore, feedback position control system or reinforcement learning are considered to be necessary in order to improve the accuracy of stop position. Although there was stop position error, Table II shows that stop positions from experiment results provided the stop positions which are closed to the ideal stop position x = 4400 mm.

VI. CONCLUSION AND FUTURE WORK

This paper presented an sensorless automatic stop control in semi-dynamic wireless charging in EV using two proposed algorithm which are command value prediction (CVP) and reinforcement learning algorithm (RLA). High transmission efficiency and short vehicular gap position is chosen to be final stop position. The feasibility of the proposed method is validated by simulations and experiments. Real-time automatic stop control experiment was implemented to validate the feasibility of command value prediction (CVP) method to control the receiver coil to stop at the high transmission efficiency position.

Future work consists of automatic stop control by more effective algorithm since the proposed method might have stop position error due to the property difference between two transmitter coils. Hence, the reliability of the proposed method can be improved by adding more transmitter coils to the system. Receiver coil uses the WPT information from multiple transmitter coils and stop at the final transmitter coil right before the intersection.

Moreover, complicated stop scene can also be considered. For examples, two-dimensional motion control ought to be considered in order to implement the practical automatic stop in electric vehicle as well. Therefore, lateral misalignment, gap length and the coil shape effect on automatic stop control performance needs to be examined in the next step of this research.

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