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An Autonomous Steering System for Wireless Charging Electric Vehicles to Minimize Power Degradation

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***Abstract*— Vehicles with wireless power transfer (WPT) is seen as one possible solution to overcome the limitations experienced in commercializing electric vehicles (EVs) due to limited battery power. However, one issue with vehicles with WPT is the power degradation that is experienced as misalignment occurs between the vehicle and the road. In order to overcome this problem, a system that can detect the misalignment between the coils and align the vehicle through autonomous steering is proposed in this paper. The concept of this system has been discussed, and simulation results validate that the proposed system's operational concept is feasible, and will be able to reduce power degradation from misalignment.**

***Keywords*— electric vehicle (EV), wireless power transfer (WPT), power degradation, coil misalignment.**

I. INTRODUCTION

The current environmental crisis that are being faced today, such as air pollution and global warming, is becoming a serious problem that cannot be ignored globally. A large portion of air pollution is caused from exhaust gases coming from vehicles, or from other forms of transport that use fossil fuel as their main source for propulsion. Therefore, various countries around the globe are publishing environmental regulations and standards that limit the amount of exhaust gases released from the vehicle. However with the currently published environmental regulations and standards, global auto manufacturers has faced difficulties generating vehicles that meet such standards solely with internal combustion engine (ICE) platforms. To make matters worse, the regulations and standards are getting stricter, which direct auto manufacturers resort to other forms of sustainable platform which can meet such strict standards [1].

The currently emerging vehicles that possess sustainable technology are electric vehicles (EVs). Many EVs have already been commercialized and can also be seen in public roads today. Electric vehicles contain a drive motor which is powered by a battery, which eliminates the need for fossil fuel. Therefore, exhaust emissions from electric vehicles can easily meet the environmental regulations and standards. However, electric vehicles possess a significant flaw that hinder customers from purchase, which is the battery technology. When comparing a vehicle with ICE and another vehicle with a battery of similar size to the ICE, the vehicle with ICE will be able to cover much more driving distance compared to the vehicle with the battery. In addition, the time to charge the battery is significantly longer compared to the time it takes to refuel an ICE platform vehicle. It can be argued that a bigger specification battery can be added to allow longer driving distances. However, bigger battery size leads to increased costs, and can lead customers to opt for ICE platform vehicles over EVs [1], [2].

To compensate the setbacks experienced from battery technologies, a research towards wireless power transfer (WPT) systems for vehicular applications has been conducted. Through this system, a vehicle can be charged wirelessly while stationary or in motion, and can significantly rely less on battery power [3]. This can reduced the amount of charging time, as well as reduce the cost of vehicle due to a smaller battery size. However, there are still limitations in applying WPT into EVs as power degradation from misalignment can be experienced while driving. As power degradation is not a desired factor, drivers must focus on keeping the vehicle aligned with the road in order to maximize the wireless power delivered to the vehicle. However, this may distract the driver from oncoming obstacles that lie ahead, and can possibly lead to potentially catastrophic accidents. In order to maximize driver's attentiveness while minimizing power degradation, a novel method of detecting the vehicle and road position, and then autonomously steering the vehicle to correct any existing misalignment is proposed in this paper. The paper is organized as follows. Section II describes the mechanism of WPT in vehicles, Section III describes the mechanism of the proposed system, Section IV describes simulation validation, followed by conclusion in Section V.

II. WIRELESS POWER TRANSFER (WPT) IN VEHICLE APPLICATIONS

A. Basic Concept of WPT

WPT is a system that can wirelessly deliver power from one system to another. This is possible through the use of generating a magnetic field by passing current through the coil. A system is usually comprised of two separate coils; a source coil, which generates and transmits power, and a load coil, which receives power from the source coil. It can be expressed through a simplified circuit diagram shown in Fig. 1. Based on Fig. 1, the voltage equation for the source coil side and load coil side are expressed as (1) and (2), respectively:

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$$\left(R_S + \frac{1}{j\omega C_S} + j\omega L_S\right) I_1 - j\omega M I_2 - V_S = 0 \quad (1)$$

$$\left(R_L + \frac{1}{j\omega C_L} + j\omega L_L\right) I_2 - j\omega M I_1 = 0 \quad (2)$$

In (1), the R_S, C_S, L_S each represents the resistor, capacitor, and inductor component in the source coil section, while R_L, C_L, L_L in (2) each represents the resistor, capacitor, and inductor component in the load coil section. The ω represents the frequency, and I_1, I_2 represents the current flowing in the source coil and the load coil, respectively. The I_1, I_2 can be further defined as shown in (3) and (4), respectively. The M is the mutual inductance between the source coil and load coil, and it is further defined as shown in (5):

$$I_1 = \frac{R_L + \frac{1}{j\omega C_L} + j\omega L_L}{j\omega M} I_2 \quad (3)$$

$$I_2 = \frac{j\omega M}{\left(R_S + \frac{1}{j\omega C_S} + j\omega L_S\right)\left(R_L + \frac{1}{j\omega C_L} + j\omega L_L\right) + \omega^2 M^2} V_S \quad (4)$$

$$M = k\sqrt{L_S L_L} \quad (5)$$

In (5), k is a value ranging between 0 and 1, and represents the coupling coefficient between the source coil and the load coil. A value closer to 1 results in a higher mutual inductance, which is a desired effect to generate higher power in WPT [4]. Based on equations (1) and (3), the source coil power can be determined as follows:

$$P_S = I_1 V_S = \frac{R_L + \frac{1}{j\omega C_L} + j\omega L_L}{\left(R_s + \frac{1}{j\omega C_S} + j\omega L_S\right)\left(R_L + \frac{1}{j\omega C_L} + j\omega L_L\right) + \omega^2 M^2} V_S^2 \quad (6)$$

Using the same technique, the power from the load coil can be determined based on equations (2) and (4):

$$P_L = I_2^2 R_L = \left| \frac{-\omega^2 M^2}{\left\{\left(R_s + \frac{1}{j\omega C_S} + j\omega L_S\right)\left(R_L + \frac{1}{j\omega C_L} + j\omega L_L\right) + \omega^2 M^2\right\}^2} \right| V_S^2 R_L \quad (7)$$

Based on equations (6) and (7), the overall efficiency of the WPT system can be determined. Using this general concept, the system can be implemented in various applications. In this paper, it is focused towards vehicular applications.

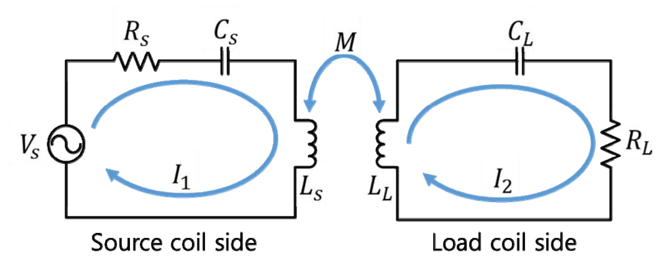

Fig. 1. Simplified circuit model for source coil side and load coil side in WPT.

Fig. 2. The currently operational online electric vehicle (OLEV), which uses WPT to charge the vehicle while stationary and in motion.

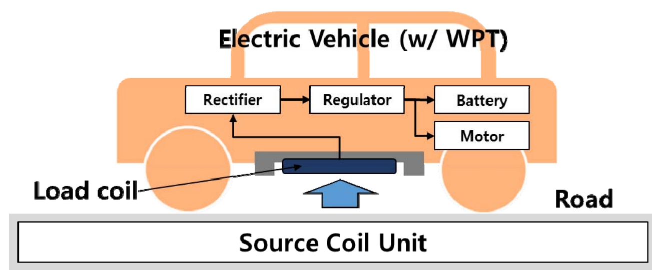

Fig. 3. A simplified block diagram that shows the configuration of an EV that uses WPT.

B. WPT in Vehicle Applications

Fig. 2 shows an example of an operational electric bus that is equipped with WPT system, which is also referred to as the Online Electric Vehicle (OLEV) [5], [6]. The vehicle shown in Fig. 2. operates around the school campus, and it is currently under progress to expand operation at other destinations. The operating mechanism of the electric vehicle with WPT is shown in Fig. 3. The source coil unit is embedded underneath the road. The source coil unit is basically a large coil, which is connected to a nearby inverter to generate current. As current flows through the source coil, a magnetic field is generated, expressed by the arrow shown in Fig. 3. The load coil, installed at the underbody of the vehicle, will receive the magnetic field from the source coil and will convert the magnetic field to voltage. The voltage is then converted into usable voltage via the rectifier and regulator, which is used to power the vehicle's drive motor and also charge the battery. However, as mentioned in the introduction, one main problem is keeping the load coil of the vehicle aligned with the source coil embedded in the road. If it is not aligned, the mutual inductance shown in (5) will drop, and will lower the power in the load as shown in (7), which creates power degradation and lower power efficiency. The amount of power that drops due to lateral misalignment can be referenced in [7].

III. MISALIGNMENT DETECTION AND CORRECTION SYSTEM FOR WPT IN VEHICLE APPLICATIONS

A. Overview

To minimize power degradation in the WPT system of the vehicle while maximizing the safety on the road, a system that can detect the misalignment between the source coil and the load coil and then adjust its misalignment between the coils through autonomous steering is proposed. The proposed system is shown in Fig. 4, where it shows a general hardware configuration inside an EV with WPT capability. The main control unit is the component that will send steering output to the vehicle based on the input references given by the load coil module and the sensor coil system. The autonomous steering function can be achieved through electronic power steering system (EPS). EPS are implemented in most EVs, and are already equipped standard in most of the recently manufactured commercial vehicles as well.

Fig. 5 shows the operational flowchart of the proposed system. The key enabler in detecting misalignment between the source coil and load coil is based on load coil voltage, which is constantly monitored through the main controller. When load coil voltage falls below a certain level, the main controller will identify that the vehicle is misaligned. In another case where the load coil voltage is near zero, the main controller will identify that source coil is no longer present, and will disable the autonomous steering function. Based on the amount of misalignment sensed through the sensor coil and load coil voltage, the corresponding steering command is given to the EPS in order to minimize the misalignment between the source coil and load coil. The explained process is repeated until the desired alignment between source coil and load coil is achieved, or if source coil is no longer present.

The components inside the proposed system are largely viewed into three parts as shown in the block diagram in Fig. 6. A detailed block diagram can be referenced in [7]. It consists of the sensor coil unit, lateral position detection unit, and the steering controller. As the vehicle is moving, the sensor coil unit will output a certain voltage waveform depending on the alignment between the source coil and load coil. The lateral position detection unit will determine whether the lateral misalignment direction between the

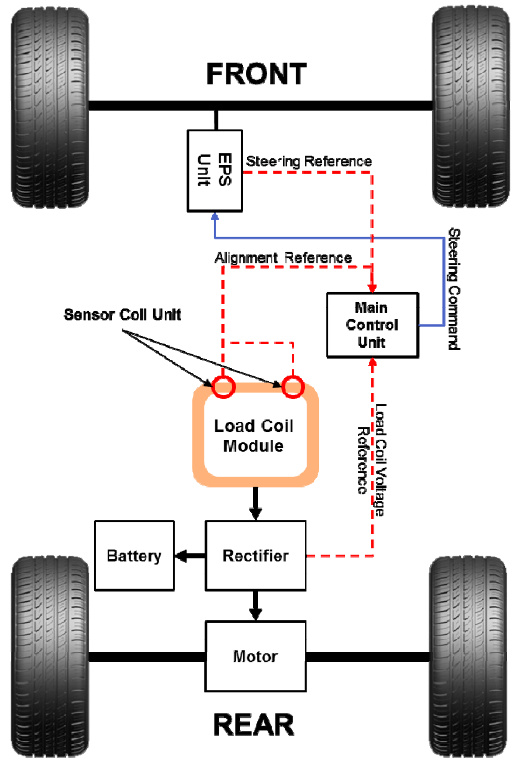

Fig. 4. Hardware configuration of the proposed autonomous steering for EVs with WPT.

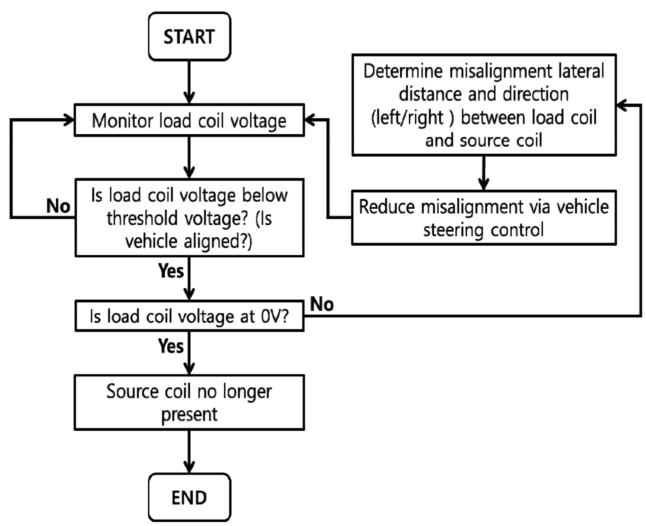

Fig. 5. Operational flowchart of the proposed system.

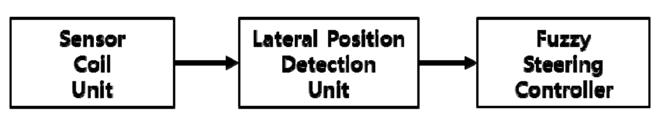

Fig. 6. Component block diagram of the proposed system.

source coil and load coil is on the left or right side. The detected location, as well as the source coil voltage value

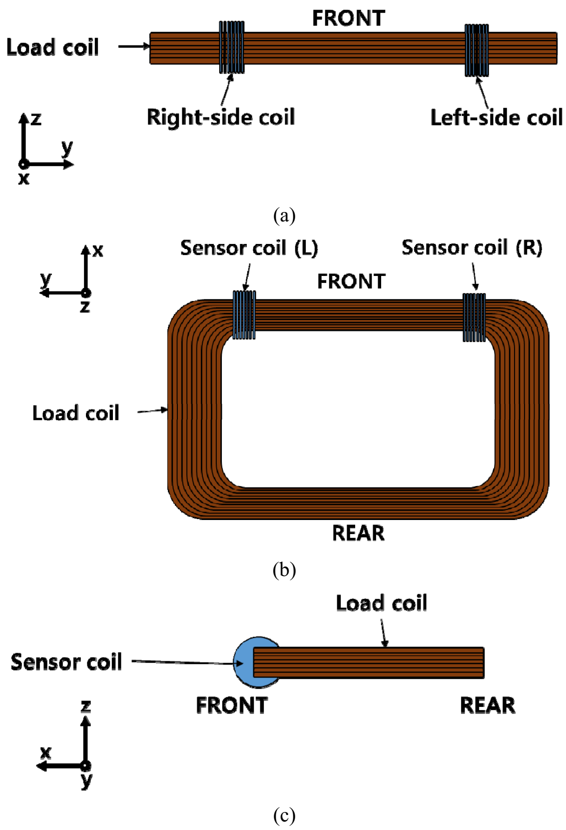

Fig. 7. Configuration of the sensor coil unit in the load coil shown in (a) front view, (b) top view, and (c) side view

will be fed into the steering controller, where the vehicle's misalignment will be corrected accordingly.

B. Sensor Coil Unit

As mentioned in the previous sub-section, the key enabler in detecting the misalignment between the source coil and load coil is measuring the voltage. The voltage is measured through two sensor coils, which are specifically attached to the front side of the load coil, as shown in Fig. 7. The two sensor coils are located at the two far-ends of the load coil, as it allows to determine the left-side or right-side location of the vehicle. Fig. 8 shows 3-D FEM simulation results as the load coil is misaligned to one side as the load coil moves away from the source coil (load coil moves towards the left side). As misalignment increases from 0 cm to 60 cm in 20 cm steps, the left side sensor coil induces a lower voltage, while the right side sensor coil induces a higher voltage, which is shown in Figs. 8 (a) through (d), respectively. Based on the simulation results, the left-side or right-side can clearly be distinguished. With the determined direction, the magnitude of misalignment is determined through the lateral position detection unit. A detailed description of the sensor coil unit can be referenced in [7].

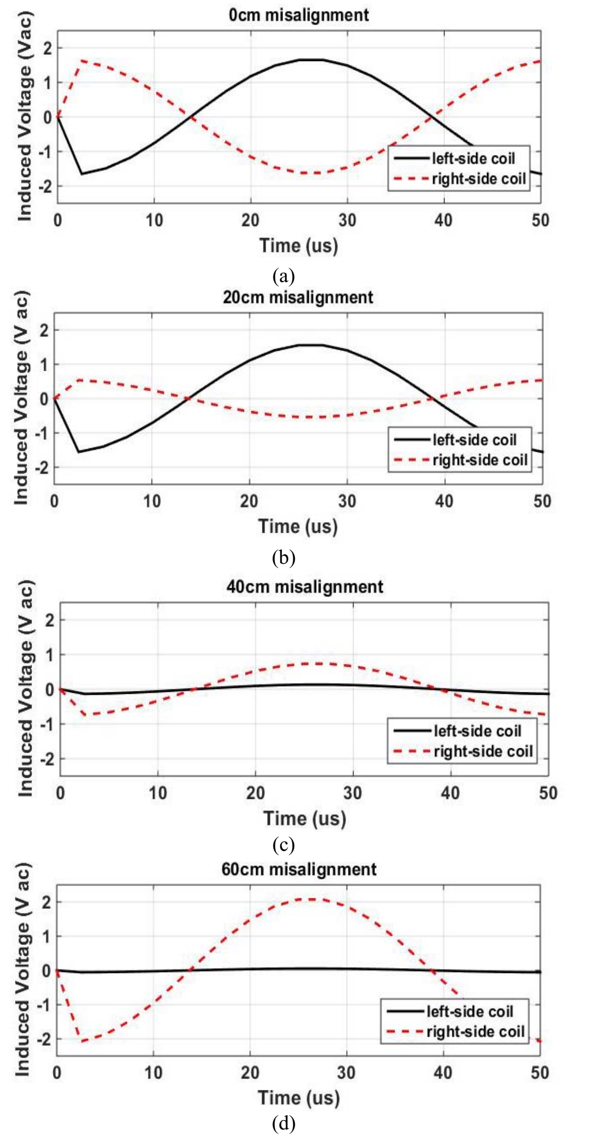

Fig. 8. 3-D FEM simulation results showing induced voltage at the left and right sensor coils as the load coil moved away from source coil at (a) 0 cm (b) 20 cm (c) 40 cm and (d) 60 cm.

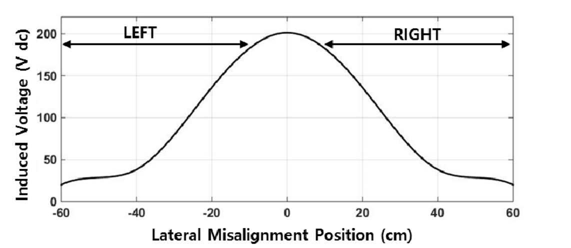

Fig. 9. 3-D FEM simulation showing induced voltage (in V dc) at load coil based on lateral misalignment between source coil in left and right direction.

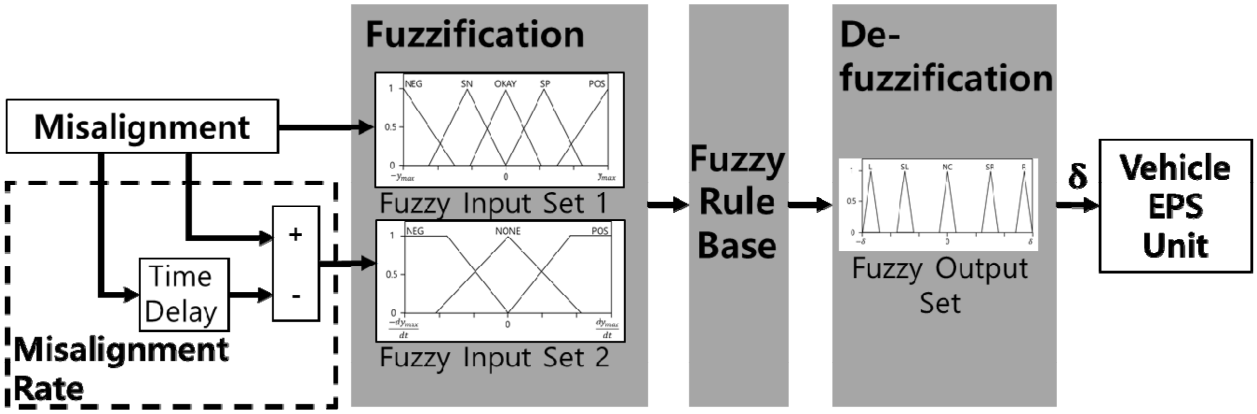

Fig. 10. The block diagram of the fuzzy steering controller used in the proposed autonomous steering system.

C. *Lateral Position Detection Unit*

In this unit, the position of misalignment is determined based on the load coil voltage reading, which can be acquired through a voltmeter. The voltmeter must be placed at the load coil's rectifier output as the voltage readings must be read in DC level. Fig. 9 shows 3-D FEM simulation results of the load coil voltage in DC level vs. lateral misalignment. Based on the simulation results, it clearly shows that increased misalignment reduces the voltage in the load coil significantly. It should be noted that this system works while the load coil is still within the range of the source coil. As the load coil moves away from the source coil, the voltage-position reference correlation becomes more complex. This algorithm can be further referenced in [7]. With the determined left or right position from the sensor coil unit, the misalignment position reference can be sent to the steering controller.

D. *Fuzzy Steering Controller*

In theory, the voltage measurements can directly be converted into position measurements which can be used to determine the amount of misalignment. However, in real world applications, various factors such as road surface irregularity, source coil design, and others generate some errors that can limit accurate control of steering using the basic principles (such as PD control). Therefore, a fuzzy logic based steering control method is used in the proposed system to tolerate such characteristics. Fuzzy logic controllers have been widely used in various control systems and they can be implemented as a non-linear controller that provides robustness over parametric and functional uncertainties, as well as disturbances [8]-[11]. The block diagram of the fuzzy steering controller is shown in Fig. 10, which follows the general configuration described in [8]. The input values will first enter the fuzzification region, where its value is approximated into "fuzzy" values. The fuzzification region has two input fuzzy sets, which are the lateral misalignment and its rate.

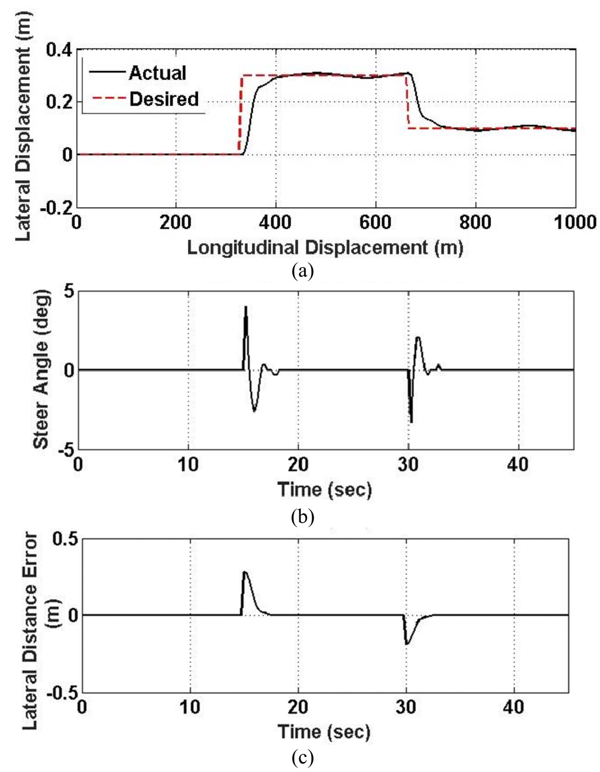

Fig. 11. Simulation results showing the performance of the fuzzy steering controller: (a) lateral displacement, (b) steering angle, and (c) lateral distance error.

The two fuzzy input sets go through the fuzzy rule base section as shown in Fig. 10, which consists of a certain rule set. Based on the two input fuzzy sets, the corresponding rule is obtained for defuzzification to generate the output steering command for the vehicle EPS unit. The defuzzification section consists of the fuzzy output set as shown in Fig. 10. A detailed design process and also the exact parameters of each fuzzy input and output set, as well as the rule base can be referenced in [7].

The performance of the controller was verified through SIMULINK, where its results are shown in Fig. 11. The simulation was conducted while the vehicle was operating at a constant velocity of 80 km/h. Fig. 11 (a) shows an X,Y grid plot, where the desired path is shown as a dashed line. A pathway with varying lateral displacement has been simulated in order to replicate a road with various source coils embedded in different lateral positions in order to force misalignment between the source coil and load coil. Fig. 11 (b) shows the steering angle magnitude, while Fig. 11 (c) shows the lateral distance error. Based on Fig. 11(c), it can be analyzed that the controller is able to detect lateral misalignment position and correct misalignment within 1~2 seconds, while maintaining a safe steering maneuver (maximum steering angle was below 5 degrees as shown in Fig. 11 (b)). Various simulation results at different speeds can also be referenced in [7].

IV. CONCLUSION

This paper has proposed an autonomous steering for EVs with WPT system as an effort to minimize power degradation due to misalignment between the source coil and load coil. The overall concept of the proposed system as well as its sub-systems were described, where the lateral misalignment is detected through the sensor coil unit and lateral position detection unit, and the detected misalignment is corrected through fuzzy steering control. Each sub-system's performance and its feasibility was verified through simulation results. The proposed system has been designed with the purpose of minimizing misalignment and maximize the wireless power delivered to the vehicle in order to maximize the driving range of the EV. It can be further developed to be used in magnetic tracking for autonomous vehicles, and can provide additional merits when using the proposed system.

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