Electric Vehicle Automatic Stop using Wireless Power Transfer Antennas

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***Abstract*—The challenge of battery's inefficiency, large and wasting space in Electric Vehicles (EVs) can be overcome by the Wireless Power Transfer technology (WPT), a technology that can electrically conduct energy from source to the electric device without interconnecting medium. Thinking one step further, the antennas that will be used in such WPT system could also be used for positioning in one-dimension as an additional benefit. This paper proposes a scheme of the positioning system using WPT antennas by considering the power gradient that the vehicle observes via the receiving antenna. PI controller is used with driving time limit to ensure safety. As an inspection for the controllers stability, simulation results are shown. Then the proposed method is implemented in the actual experimental system. The results show that, with the proposed method, the vehicle can be stopped at the position with maximum received power. The system can also be applied to parking areas with limited space or difficulty in positional awareness such as in tight space or slope surface, drive-through paying booth, e.g., tollways, where the drivers are assisted to stop the car appropriately.**

I. Introduction

Wirelessly powered electric vehicles have been researched for decades. Maglev system, [1], is an example of such system that has been researched since late 1970s; it utilizes the high speed nature of the traveling vehicle to generate electricity using linear generator. On-line Electric Vehicle (OLEV) system, [2], which is developed by KAIST, made its debut in early 2009. The research in [4] proposed a wireless charging system for EVs with circular coil antennas. [3], [4] allow energy transmission at high efficiency with moderate air gap, more importantly, no cryogenic coolant is required and deemed practical by experiments and routine operations.

The Wireless Power Transfer System works from a high frequency energy source connected to a transmitting antenna. Then, the transmitting antenna wirelessly conducts energy to the receiving antenna. From that receiving antenna, a power electronics circuit rectifies the incoming waveform and then store the energy into the energy storage unit. Figure 1, from [4], shows the overview of the system.

With the two antennas from the WPT system installed on the road and on the vehicle, position control can be done without knowing the exact value of the received power strength at the receiving antenna on the vehicle, only power gradient and simple PI controller is utilized. Furthermore, since the exact value of the received power strength is not needed, the system becomes robust against the disturbances in the received power strength.

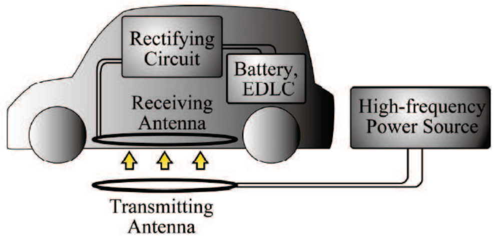


Fig. 1. Overview of Wireless Energy Transfer for EV

This paper is organized in sections. The previous works and paper overview is introduced in Section I. Then, the experimental setups, the vehicle and the WPT system are explained in Section II. Section III explains the problem statements and the proposed methods in each of the control scenarios. Results, discussions and possible applications are presented in Section V. Then, simulation results of a motion control of a two-dimension system are showed and explained in Section IV before continuing to conclusions in Section VI.

II. Experimental Setups

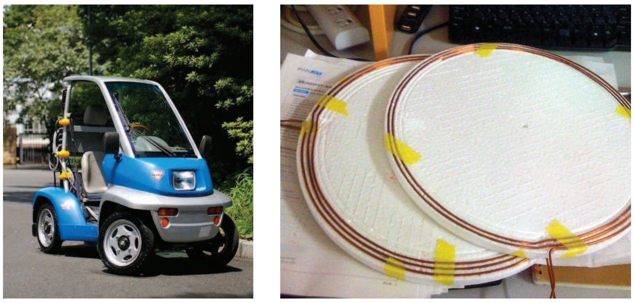
This section describes the plants that will be controlled. The plants comprise of an electric vehicle and a WPT system, which will be explained in subsection A and B, respectively.

A. Electric Vehicle (EV)

The experiment vehicle used in this study is COMS1, a capacitor driven EV based on Toyota's COMS platform which is developed for motion stability researches. COMS1's development is described in [6]. The photo and specifications of COMS1 are showed in the Figure 2 and Table I, respectively.

The EV can be modeled as the transfer function

$$P_{vehicle}C_{vehicle} = \frac{k}{rms} \quad (1)$$



(a) COMS1 (b) WPT Antennas

Fig. 2. Experimental setups

TABLE I
COMS1 SPECIFICATIONS

Parameter	Value
Classification	Single-Seater Small-Size Electric Car
Drive System	Two Rear-Driven In-Wheel Motors
Motor (Maximum Rating/Rating)	IPMSM (2kW/0.3kW)
Inverter	PWM Vector Control (MOSFET)
EDLC Voltage/Capacity/Capacitance	210V/173Wh/29.3F (2P14S)
Dimension/Weight	1935 x 995 x 1600mm/310kg
One-Charge Mileage /Running Timer[1]	4 - 5km/20 min
Charging Time[2]	Approximately 30 seconds
Real-Time OS	Advanced Real Time-Linux
Controller	Single Board Computer (SBC) PCM-9371 SBC
A/D Convertor	TAC Inc., T104-ADA

where k, r, m and s are the error signal-torque gain, driving wheel radius, and mass of the vehicle, Laplace operator, respectively. $C_{vehicle}$ and $P_{vehicle}$ are shown in Figure 3 (b).

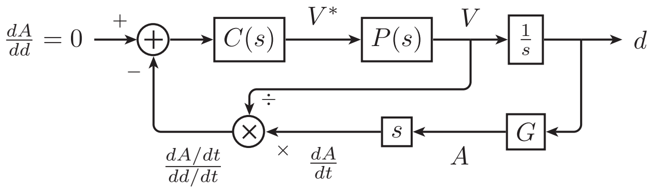
The error signal-torque gain, k in Figure 3 (b), is the gain that transfer velocity error signal in closed loop controller into torque command inside the controller $C_{vehicle}$. When the vehicle is in the velocity-control feedback loop, the transfer function of the electric vehicle plant, $P(s)$, is

$$P(s) = \frac{P_{vehicle}C_{vehicle}}{1 + P_{vehicle}C_{vehicle}} \quad (2)$$

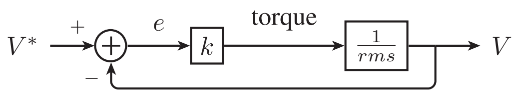
$$= \frac{k}{k + rms}. \quad (3)$$

$P(s)$ is also shown in Figure 3 (a) with detailed structure in (b). Figure 3 (a) represents the system in this research. In Figure 3 (a), A, d, $C(s)$, V^*, $P(s)$, V, G, t are antenna's recieved amplitude, relative horizontal position of recieving antenna with respect to transmitting antenna, position controller, desired velocity, vehicle plant, actual velocity, WPT plant, and time, respectively.

[1]Driving speed around 12 km/h.
[2]More than 20% SOC at 150 A charging.



(a) Whole system



(b) Vehicle plant, P

Fig. 3. Block diagrams.
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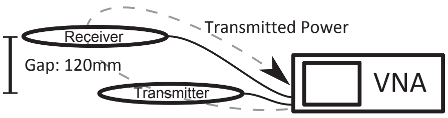
B. Wireless Power Transfer System (WPT)

Environment referencing is needed in position control of any kind; while other position control systems may use LIDAR, RADAR, Ultra Sonic sensor, etc., to gauge the distance of the object-under-control to the environment, hence the position, this system senses its position via the characteristics of WPT antenna which change its mutual inductance with the distance moved, in turn changes its receivable power.

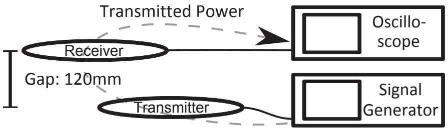
A way of detecting efficiency of transmission in a electromagnetic network is by looking at scattering parameters. In multiport electromagnetic network, scattering parameters represent the ratio of power obtained from one port that is the resulting from the input from the other port, e.g., S_{21} is a scattering parameter representing the ratio between output power from port 2 and the input power to port 1. The antenna system in this research can be think of as a two-port system. Let port 1 and port 2 be the ports that connect to power source, and sensing system, respectively. In Figure 4 (a) both ports connect to VNA, while in (b), power source and sensing system are signal generator, and oscilloscope, respectively. S_{21} is transmission coefficient because it represents the output from port 2 from input at port 1; how much the power is transmitted. In the same way, S_{11} is referred to as reflection coefficient as it measures the output from port 1 as the effect from the input from the same port.

Received power gradient, the differential of received waveform amplitude with respect to position, is used for position control. To study power pattern at different displacement of the antennas, a Vector Network Analyzer (VNA) is used. Configuration in Figure 4 (a) is used to obtain the received power at different distance, d, that the vehicle travel at air gap of 120 mm. The result of transmission coefficient or the scattering parameter, S_{21}, is obtained as in Figure 5 (a).

Please note here that the transmission coefficient, S_{21}, curve, similar to one in Figure 5 (a), with this antenna type, will occur only when the distance between the transmitting and recieving antennas, the air gap, is less than the diameter. Otherwise, the peak that can be observed at poistion 2 in Figure 5 (a) will be moved to the position d = 0 mm, hence only one large peak exists, no valley at poistion 3 in Figure 5

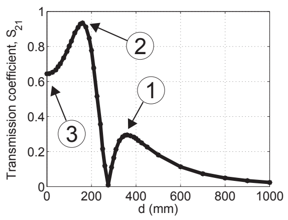


(a) System with a Vector Network Analyzer

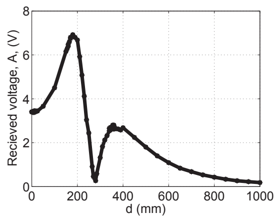


(b) System with a Signal Generator and an Oscilloscope

Fig. 4. Experimental Wireless Power Transfer setups.



(a) System with a Vector Network Analyzer



(b) System with a Signal Generator and an Oscilloscope

Fig. 5. Measured received power.

(a). In EV application, the later case would not occur since the underside of vehicle would not be that high.

Even though VNA gives very accurate output, it has expensive cost, slow response time, and requirement of two coaxial wires to connect the system, from both transmitting and receiving antennas, to the VNA. These reasons render VNA unattractive for this application.

With the mentioned limitations of VNA, an alternative configuration using two separated units, i.e., signal generator and an oscilloscope is presented. This new system uses a signal generator to feed high frequency signal at 13.56 MHz to the transmitting antenna. The receiving antenna is connected to oscilloscope to measure the received waveform. The amplitude in the received waveform is considered to infer the received power because power and waveform amplitude is related according to the relationship

$$A^2 \quad \propto \quad P \tag{4}$$

where A and P are the amplitude of the waveform and the power, respectively.

The configuration and the pattern of the received power in this new system are shown in Figure 4 (b) and Figure 5 (b), respectively. Figure 5 shows compliances between the system with VNA and with the signal generator and oscilloscope. Therefore we can use the system in Figure 4 (b) to sense the received power. The groove of the zero power exhibited in Figure 5 is caused by the characteristic of the antenna itself. The differences between the position of the peaks and valley in the two measuring systems, shown in Figure 5 (a) and (b), are noticeable; the peak can be moved closer or further away from the origin by controlling electrical load in the system in Figure 4 (b) to match that of VNA.

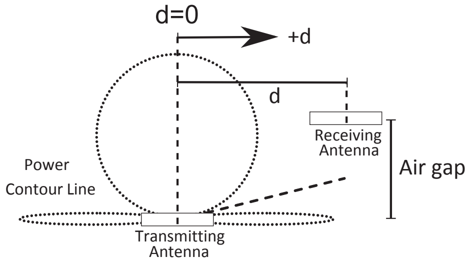


Fig. 6. Radiation pattern of the antenna.

The antennas used in this research are of open type, double spiral copper coil with the outer radius of 150 mm, 5 mm pitch and for 5 windings. The general radiation pattern of antenna of this type can be depicted in Figure 6. Fine dash lines and dash line in Figure 6 show power contour and zero radiation contour, respectively.

Due to the government regulation, only frequencies in ISM (Industrial Scientific Medical) band are allowed. This particular system is design for 13.56 MHz range with antenna dimensions suitable for implementing in vehicles because the lower allowed band is in several kHz ranges which may requires antennas and clearance space of 500 mm.

The system mechanism can be explained as following. First, 13.56 MHz signal from signal generator is fed into the transmitting antenna which is in resonance with the identical receiving sides antenna. The sinusoid waveform is then appeared in the receiving coil and can be observed by an oscilloscope. Since only the amplitude of the waveform is needed, a Full-Bridge rectifier circuit is used. To obtain the cut-off frequency at relatively low at 99.5 kHz, diode, capacitor, and the resistor are 1SS196, 1 nF, and 1.6 kΩ, respectively. In this experiment, an A/D converter in COMS1 is used to sense the amplitude of the received waveform from the receiving antenna attached to the vehicle. Sampling period of the A/D converter is 8 μs. In this experimental system, small power with maximum at 1 W, signal generator limit, is used; Actual powering powering at 1 kW or more is neither covered nor utilized in this research.

III. Problem Statement and Proposed Method

Scope of the works in this paper and the proposed solutions are presented in this section.

A. *Problem Statement*

Parking can be burdensome for some driver as the process involve maneuvering the vehicle in tight space with precision, hence automating the process to stop the car at a suitable position is promising. Also, with the invention of Wirelessly Charged EV, stopping the vehicle where it could get the maximum power is a desirable application.

This paper presents two objective of automatic position control: for *maximum power transfer* and for *positioning* (aligning receiving antenna directly above the transmitting antenna.)

B. Proposed Method

The controller is designed to be robust against the noise from measuring the input waveform amplitude. PI controller is used together with time limitation of the maneuver. The proposed control method is divided into following steps.

1) For the maximum power transfer objective: the vehicle should stop at position 2 in Figure 5 (a). This can be done by:

- Use PI Controller with the differential of received amplitude with respect to position, dA/dd, as the reference signal to bring the vehicle to the position 1 in Figure 5 (a).
- Maneuver the vehicle across the gap to the slope close to position 2 in Figure 5 (a).
- Execute the same PI Controller to bring the vehicle to position 2 in Figure 5 (a).

An experiment will be conducted to demonstrated this objective. The results are in Figure 8.

2) For the position control objective: the vehicle should stop at position 3 in Figure 5 (a) which makes the receiving antenna stay directly above the transmitting antenna. The method is:

- Follows the maneuver in objective 1).
- Move the vechile further close to position 3 in Figure 5 (a).
- Apply another PI Controller to move the vehicle to where it gives local minium received power, i.e., position 3 in Figure 5 (a).

The PI Controller, taking the differentiation of waveform amplitude with respect to position, dA/dd, as the control input and output desired vehicle's velocity, V^*, is given by

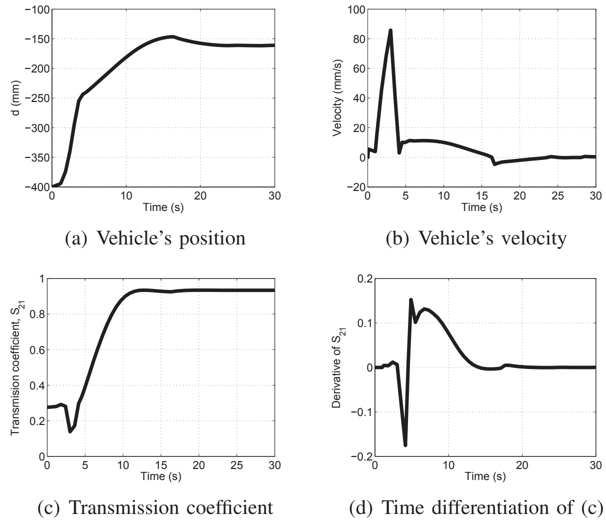
$$C(s) = \frac{V^*}{dA/dd} \quad (5)$$

$$= \frac{K_i + sK_p}{s} \quad (6)$$

where V^*, dA/dd, K_p, and K_i are desired vehicle's velocity, differential of waveform amplitude with respect to position, proportional gain, and integral gain, respectively.

In actual implementation, a low-pass filter with large time constant is applied to the obtained amplitude readout to reduce measurement noise.

The stability of the whole system, including the simulated antenna system, is then confirmed by simulation in MATLAB Simulink. The simulation results of the method for the maximum power transfer objective is shown in Figure 7. The results in Figure 7 use parameters K_p, K_i, k, r, m, and τ at 1, 0.001, 3000, 21 mm, 350 kg, and 0.02 s, respectively. A signum function is also used after the controller, $C(s)$, to compensate the vehicle inertia.



(a) Vehicle's position (b) Vehicle's velocity (c) Transmission coefficient (d) Time differentiation of (c)

Fig. 7. Simulation results of the method for Maximum Power Transfer.

IV. Results and Discussions

Figure 8 shows the result of an experiment for maximum power transfer objective. Figure 8 (a) shows that the received voltage, A, which is proportional to the square root of the received power. Figure 8 (b) show the controllers reference signal, the differential of received amplitude, dA/dd. Figure 8 (c) shows the position of the vehicle, d, with time.

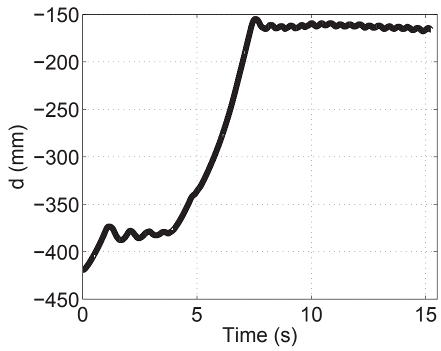
Figure 8 (b) shows that the proposed controller can bring the vehicle to the position with maximum received power in 8 seconds after the controller is deployed. One might notice the small position fluctuation after the vehicle reach the optimum position. The fluctuation comes from the position fluctuation as being showed in Figure 8 (a), which is also visible. Since the position control in this research takes dA/dd as the reference signal, the fluctuation in Figure 8 (a) and (b) could be explained by the fluctuation of the dA/dd showing in Figure 8 (c).

From Figure 8 (a), the controller moved the car from about –420 mm to the first peak, point 1 in Figure 5 (b), by around 2 seconds at about the position –380 mm, and after that, the large peak, point 2 in Figure 5 (b), by 8 seconds at around –160 mm position and stay there.

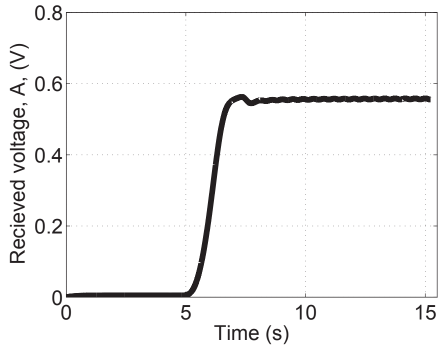
The un-diminishing fluctuation showing in all figures in Figure 8 is the result of the signum process that aimed to compensate the vehicle frictions and bring the vehicle to the good position faster. The drawback is resulted in the fluctuation. There is a strategy to counter the fluctuation if signum is in-place by disable the controller after the early fluctuations is detected.

With this system successfully implemented, the possible applications include maneuvering vehicle which requires drivers attention, e.g., stopping a vehicle at drive-through, parking close to walls/dangerous physical limits, or parking on slant roads.

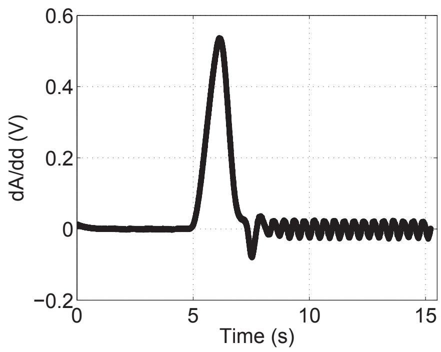
In addition, noise problem can be reduced by using elec-



(a) Vehicle's position



(b) Received waveform amplitude



(c) Time differential of (b)

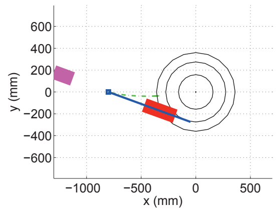
Fig. 8. Experimental results.

trical components that support higher frequency or designing the system to work at lower frequency, i.e., kHz range.

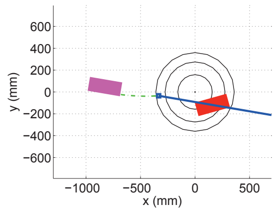
This work has shown that a contact-less position control using WPT antennas is possible. The next steps are to expand the area of applications to wider range. Another possible application would be controlling lateral position of the vehicle in lane-keeping application which would realize the WPT infrastructure better and promote better security to the passengers themslves, and pedstriants who are close to the vehicles.

V. Simulation of Two-Dimension System

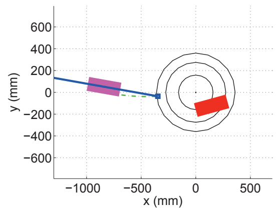
In order to inspire the readers with the possibility of applications mentioned, a simulation with two-dimensional



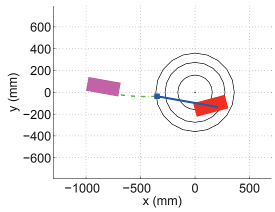
(a) Vehicle at 0 second.



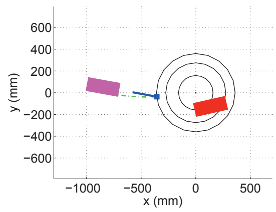
(b) Vehicle at 9.7 seconds.



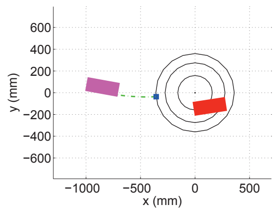
(c) Vehicle at 10.6 seconds.



(d) Vehicle at 12.5 seconds.



(e) Vehicle at 16.0 seconds.



(f) Vehicle at 20 seconds.

Fig. 9. Two-dimensional geometry simulation results.

motion is demonstrated. The objective of this demonstration is to show that other applications are also possible.

This demonstration use the same PI controller demonstrated for the one-dimensional case. The system use one receiving and one transmitting antenna each to sense the power received. The challenge then comes when a good controlling strategy is needed to bring the vehicle to the right position.

The controller about to be demonstrated has a basic objective to bring the vehicle to stop at the position with first highest received power it meets, and stay there.

With only one input signal, the received amplitude, A, the controller must outputs two control variables, desired vehicles velocity, V^*, and desired steering angle, δ^*. Hence, the proposed controller has two parts: *velocity controller* and *steering controller*.

Velocity controller uses a PI controller to bring the vehicle to its destination while steering controller is more complex as shown in equation 7, and 8, respectively. The simulation results are shown in Figure 9.

$$V^* = \{k_{pv} + k_{iv}/s\}\frac{dA}{dd} \quad (7)$$

$$\delta^* = \frac{k_\delta}{s}\frac{d\frac{dA}{dd}}{d\psi} \quad (8)$$

The bicycle model represents the vehicle to simulate the system in MATLAB Simulink. In equation 7, k_{pv}, k_{iv} and dA/dd

are the PI controllers proportional and integrational gain and controller input, differential of received amplitude with respect to vehicles position, respectively. And in equation 8, ψ, k_δ are the vehicles heading angle and the proportional gain, respectively. The simulation takes parameters k_{pv}, k_{iv} and k_δ at 100, 10 and 6, respectively. The simulation results are shown in Figure 9.

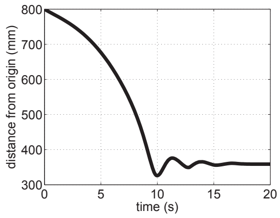
Please notice that the controller used in this two-dimention simulation, unlike one used in previous experiment, is one-step controller, i.e., this controller will not bring the vehicle to stop at the inner highest peak, position 2 in Figure 5 (a), but only the closest peak it encounter, position 1 in Figure 5 (a).

Figure 9 (a), (b), (c), (d), (e) and (f) are captured at 0, 9.7, 10.6, 12.5, 16.0 and 20 seconds, respectively. The outer, and inner circle in Figure 9 are peaks corresponding to point 1, 2 in Figure 5 (a), respectively. In the same way, the middle circle represent the valley between point 1 and point 2 in Figure 5 (a). Thick blocks represent vehicle's wheels. Right bolck (red) repreents front steering wheel, while another is rear wheel. A small square (blue) lying at the middle between the front and rear wheel is the vehicle's center of gravity, CG, which wanted to be moved onto the outer circle contour line. The line section (blue) growing from vehicle's CG has its length corresponding to the vehicle's velocity so readers can see when the vehicle is stop. The dash-dot line (green) shows the vehcle's trajectory.

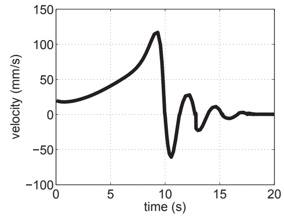
At the beginning of the simulation, shown in Figure 9 (a), the center of gravity of the vehicle is at the position x = –800 mm and y = 0 mm and tilted downward 20°.

For the end of the simulation, shown in Figure 9 (f), the center of gravity of the vehicle is on top of the outer circle denoting a peak contour. This proofs the controller succeeded in bringing the vehicle to the position with maximum transferring power.

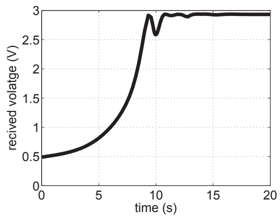
Figure 10 shows the same simulation in graphs with time as the x axis. From Figure 10 (c), the increasing receiving voltage representing the power transfer efficiency can be noticed. Figure 10 (b) shows the velocity of the vehicle; the velocity is fluctuating in both positive and negative regions showing forward and backward motion to bring the vehicle to the final position. Figure 10 (a) let us appreciate the motion of the vehicle that it come to the rest at the distance 367.10 mm from the origin, the peak position. Figure 10 (d) show the adjustment of vehicle heading angle, ψ.



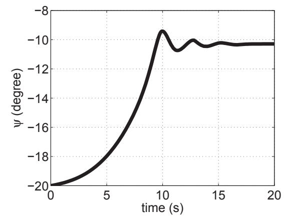
(a) Vehicle's distance from origin



(b) Vehicle's velocity



(c) Received waveform amplitude



(d) Vehicle's heading angle

Fig. 10. Two-dimension system simulation results.

VI. Conclusions

In EV, expensive-inefficient battery usage can be reduced by using On-line Wireless Power Transfer (WPT) System. Eventhough this research used low power experiment, it goes one step further to another application of WPT in addition to power vehicles. A scheme of controlling vehicle to stop at a position with antennas as the position markers is proposed and demonstrated in simulation and experiment. Such positioning system is applicable in both positions homing and position control to achieve maximum charging power, hence the efficiency. The controller used demonstrated robustness against fluctuations in measured received waveform amplitude as the exact value of the recieved amplitude is not needed at all. Applications of this system include, but not limit to, position control where special attention would be drawn, such as parking in tight space or on a slant road.

WPT for EVs at higher wattage is still a hot topic in research.

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