Human-Vehicle-Interaction System with Unmanned Driving EV in Parking Lots by Impedance Control

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The unmanned driving of electric vehicles (EVs) is getting attention, but its practicality in places where many people and vehicles come and go, such as parking lots, is still low. In light of such a situation, the authors propose a control method for realizing a human interface for unmanned EVs by applying impedance control, which is generally used for robots, to EVs. This control method allows humans to stop an unmanned EV by hands easily and predictably. In the end, the effectiveness of the proposed method is demonstrated by simulation and experiment.

Keywords: Electric Vehicle, Impedance control, Vehicle motion control, In-Wheel-Motor, Unmanned driving vehicle

1. Introduction

1.1 Widespread use of EV and its research In recent years, electric vehicles (EVs) have been attracting attention because they are more environmentally friendly than conventional gasoline-fueled vehicles in that they do not emit greenhouse gases, and they have the advantage of excellent control performance because the response speed of electric motors is about 100 times faster than that of gasoline-fueled vehicles.

Taking advantage of these characteristics, anti-slip control to suppress slippage on low-μ roads, driving force control [2], and hand-assisted control [1] have been studied in our group.

1.2 EV calling feature and its problems In addition, a feature called "Smart Summon" in Tesla cars is getting attention [12]. This feature allows drivers to call the Tesla cars with a smartphone or other device and they automatically come to drivers. This feature is already in effect in some countries, but has some problems. In order to avoid hitting people, the system is designed to stop the car as soon as the camera detects a person. For those reasons, it is not practical in places where many people and vehicles come and go, because vehicles stop every time they detect a person.

1.3 The purpose of this research Based on the aforementioned current situation, in this research, the authors propose a control method that realizes the human interface of EVs, such as the ability to stop and move easily by touch. Specifically, a soft motion that is predictable by humans is achieved by controlling the motion of unmanned EVs using the estimated value of the external force which is applied by human hands. Such a controlling method will solve the problem of the current Smart Summon vehicles that stop immediately when they detect a person in the distance, and safe unmanned driving will be achieved even in crowded places such as parking lots.

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Figure 1: Experimental device : FPEV-2 Kanon

2. Experimental Device and Modeling of EV

The experimental setup and its physical model are shown in this section.

Table 1: specifications of FPEV-2 Kanon

Parameter	Value
Vehicle mass M	870 kg
Inertia of a front wheel J_f	1.24 kg m^2
Inertia of a rear wheel J_r	1.26 kg m^2
Wheel radius r	0.302 m

2.1 Experimental device Figure 1 shows the vehicle used in this research, FPEV-2 Kanon, and its specifications are shown in Table 1. The vehicle has outer-rotor type in-wheel motors and each wheel can be controlled independently. The control performance is high because the torque of motors is immediately transmitted to the wheels.

2.2 Modeling of EV The physical model of EVs can be represented by (1) by assuming below :

- Slip ratio is 0 because the vehicle speed is low
- Vehicle driving is straight ahead only

$$\frac{\omega}{T} = \frac{1}{(J_\omega + r^2 M)s} \quad (1)$$

3. Impedance Control and Hand-Assisted EV Control

In this section, the overview of impedance control and a

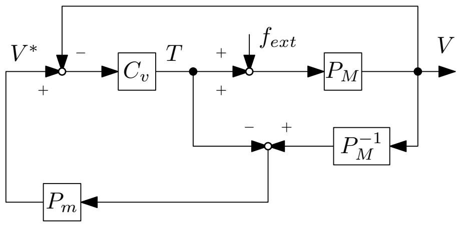


Figure 2: Typical force sensorless impedance control system.

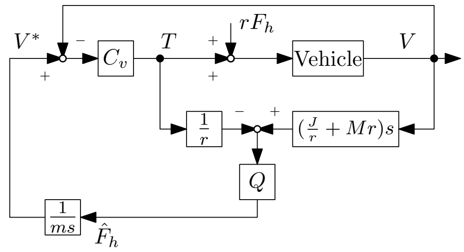


Figure 3: Control system of hand-assisted control

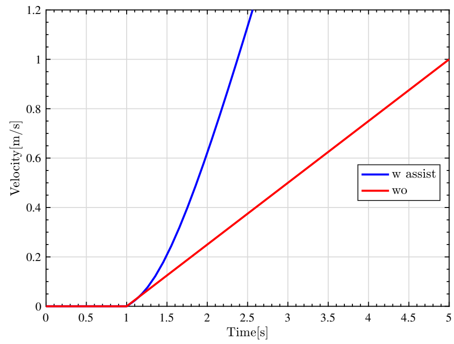


Figure 4: Simulation of hand-assisted control : V

previous research which is applying impedance control methods to EVs are introduced.

3.1 The overview of impedance control Impedance control is a control method to make the mechanical impedance such as inertia, damping constant, and mass to the external force to be a convenient value for the desired operation. The control method is generally used in robots control, such as industrial robots that perform contact work such as grinding and assembly, medical and welfare robots, and amusement robots that directly interact with people. Although much research has been done to realize human-friendly behavior using impedance control [3] [4] [5] [6], their targets are mainly robots. There are few studies that attempt to apply impedance control to EVs, except for Enmei et al.'s works on hand-assisted control [1].

3.2 The application of impedance control to hand-assisted control The overview of hand-assisted control is introduced. The hand-assisted control aims to assist the hand-push of the EV by using impedance control so that the EV can be moved with a small amount of force, and realize human-friendly EVs.

Figure 2 shows the system of velocity-based impedance control by external force estimation without using any force sensors. In this system, external forces are estimated by disturbance observer (DOB). The velocity reference is obtained by inputting the estimated value into the impedance model. Thereby, it is achieved that the plant behaves as if it has the characteristics of the desired impedance model.

The application of the impedance control to EVs hand-assisted control is introduced. Figure 3 shows the system. Q is low pass filter (LPF).

Velocity controller is designed by PI controller and means of pole placement.

The value of external force is estimated by the below.

$$\hat{F}_h = \frac{1}{r}\left((r^2 M + J_\omega)\omega s - T\right) \cdots\cdots\cdots\cdots (2)$$

Using the estimated value, the velocity reference is calculated by the below.

$$V^* = \frac{\hat{F}_h}{ms} \cdots\cdots\cdots\cdots (3)$$

This allows the EV to behaves as if its mass is m.

Figure 4 shows the results of velocity simulation where the cutoff frequency of LPF is set to 10 rad/s, mass of EV is $M = 800$ kg, target apparent mass of the EV is $m = 200$ kg, and poles of PI controller is set to 3 rad/s. Figure 4 shows that vehicle moves faster when the assist control is added although the same force is applied.

4. Application of Impedance Control to Unmanned Driving EV

4.1 Problem setting In light of the problems of unmanned EVs described in the introduction section, the authors set the goal of creating a human-friendly interface for unmanned EVs. In this research, the authors propose a control algorithm which realizes vehicle motions that human can stop easily and naturally by hands, and start running again in a natural way when the hands leave the vehicle. For simplicity, it is assumed that the vehicle moves only straight at a constant speed.

The most basic algorithm to realize such motions would be, for example, the system shown in Figure 6. This is a method of switching the velocity reference value so that the vehicle stops when the external force exceeds a certain value (F_0), and runs as usual otherwise, as shown in the following equation.

$$V^* = \begin{cases} V_0 & \left(\hat{F}_h > F_0\right) \\ 0 & \left(\hat{F}_h \le F_0\right) \end{cases} \cdots\cdots\cdots\cdots (4)$$

However, there is a problem with this method. In this algorithm, when the vehicle is stopped, it suddenly starts running the moment the external force falls below F_0, or the running velocity does not change until it exceeds F_0 even if the force is applied to stop the running EV. This is not a natural behavior.

In this research, the application of the impedance control to unmanned EVs is proposed, and the effectiveness in terms of realizing the interface described above is shown.

4.2 Control algorithm Figure 7 show the proposed system. Note that V_0 is the velocity during normal unmanned driving and that P_m is the impedance model as shown below :

$$P_m = \frac{1}{ms + b} \cdots\cdots\cdots\cdots (5)$$

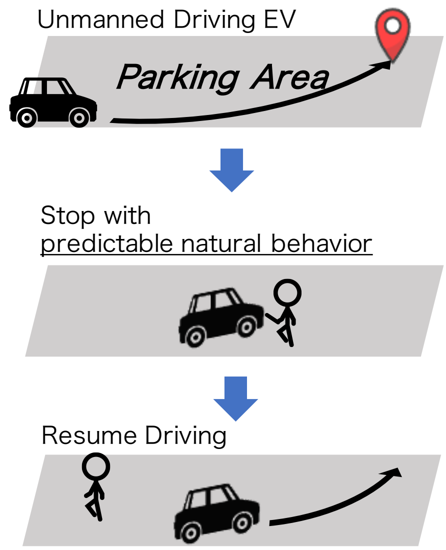


Figure 5: Problem setting in this research

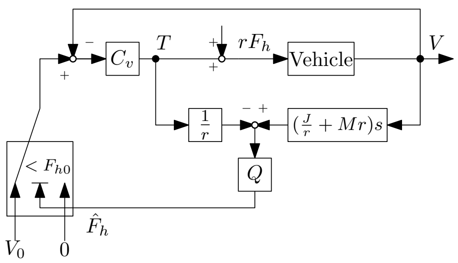


Figure 6: Control system of switching algorithm

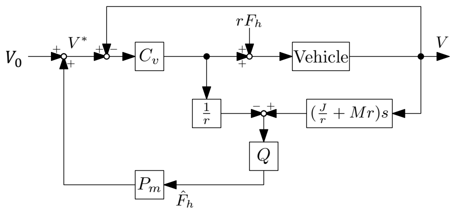


Figure 7: Control system of proposed method

where m is target apparent mass, and b is apparent damping constant. Velocity reference is calculated as below :

$$V^* = V_0 - \frac{\hat{F}_h}{ms+b} \quad \cdots\cdots (6)$$

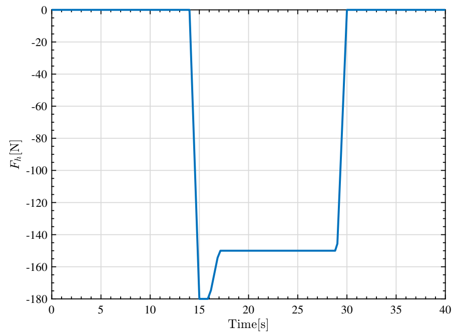
As can be seen by transforming (6) into the following equation of motion, a person pushing an unmanned vehicle by hand to stop it will feel as if an external force of $V_0 b$ is being applied in the opposite direction, and the vehicle has mass m and damping constant b.

$$(ms+b)v = V_0 b - F_h \quad \cdots\cdots (7)$$

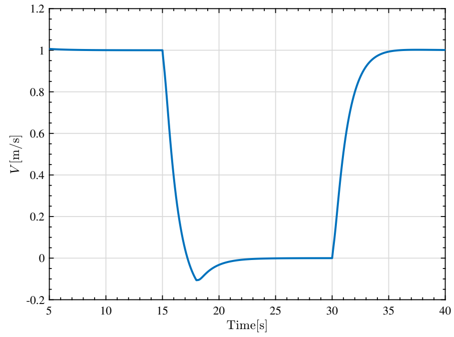
5. Simulation

In this section, the following two simulations on an unmanned EV running at 1 m/s are conducted, and the effectiveness of the proposal is shown.

5.1 Simple external force simulation The velocity simulation of the external force as shown in Figure 8a is conducted. At 14 s, applying an external force begins, which is



(a) F_h



(b) V

Figure 8: Simulation of simple external force simulation

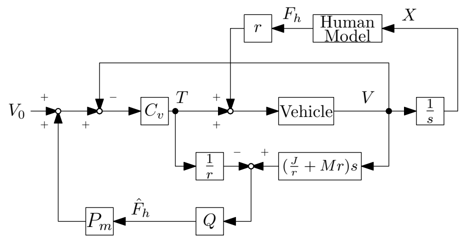


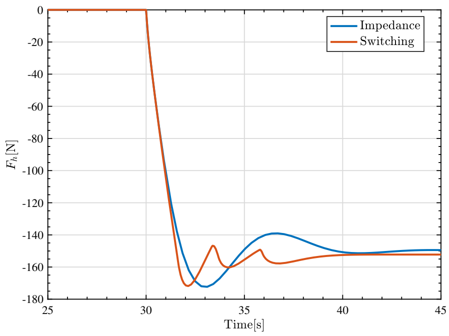
Figure 9: Simulation with human impedance model

larger than the balancing force because human is trying to stop the moving vehicle, but as the speed decreases, force is gradually reduced and converges to the balancing force, and then at 29 s, human takes its hands off the vehicle. Impedance model is designed with $m = 200$ kg, $b = 150$ kg s. Figure 8b shows that the velocity is 0 m/s while the external force is applied.

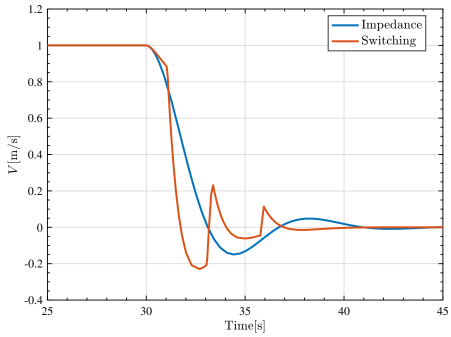
5.2 Simulation with human impedance model The external force applied by human to the vehicle is assumed to be an impedance model, and simulations were conducted as shown in Figure 9. There has been a lot of studies on analyzing human impedance characteristics [7] [8] [9], and it is known that the impedance characteristics of humans in interactive tasks with robots can be represented by the following damping-stiffness model

$$f = -D\dot{x} + K(x_d - x) \quad \cdots\cdots (8)$$

where D is human damping constant, K is human stiffness, and x_d is the target position intended by human. In this simulation, external force according to distance error is supposed $K = 100$ N/m at first, and then, D is supposed 20 N s/m to reduce vibration to some extent. Figure 10a and Figure 10b show results of the velocity and external force simulation. As shown in these, the proposed method has less vibration and



(a) F_h



(b) V

Figure 10: Simulation of human impedance model

Figure 11: Experiment of estimating external force

gives people a sense of security.

6. Experiment

In this section, it is confirmed that the external forces could be estimated accurately by DOB at first, and then, the effectiveness of the proposed method is verified by experiments.

6.1 External force estimation by DOB The experiment is conducted by pulling the running EV from behind with a rope as shown in Figure 11 for safety reasons.

Figure 12 shows the estimate of the external force filtered by LPF(ω_p = 3 rad/s) and data with compensation for driving resistance. During the period from about 0 s ~ 1.5 s, the vehicle is at a standstill; during the period from about 1.5 s ~ 5 s, the vehicle is running normally without external force; during the period from about 5 s ~ 10 s, external force is applied; and during the period from 10 s ~ 11 s, the vehicle is running normally again. Driving resistance is assumed as below

$$F_{DR} = \begin{cases} -F_A & (\omega_0 < \omega) \\ -\frac{F_A}{\omega_0}\omega & (-\omega_0 \leq V \leq \omega_0) \\ F_A & (\omega > \omega_0) \end{cases} \quad \cdots\cdots\cdots\cdots (9)$$

for these reasons.

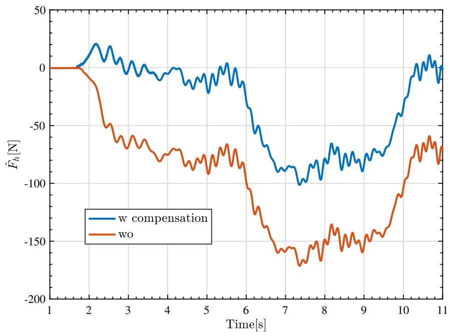


Figure 12: Experiment results of F_h estimation

- In the low speed range, the resistance is dominated by the rolling resistance, which is a constant that depends only on the positive or negative speed.
- To prevent sudden changes in the estimated value at the velocity sign transition point

ω_0 = 1.6 rad/s and F_A = 70 N are used based on the results of previous measurements.

Figure 12 shows that external force is accurately estimated to some extent.

6.2 Experiment of proposed method The experiment is conducted in which the vehicle running at a constant velocity is pulled to stop by a rope from behind. The running speed is set to 0.5 m/s, and the controller is designed by means of pole placement with ω_p = 1 rad/s. The impedance model is designed with m = 200 kg and b = 200 kg s.

Figure 13a and Figure 13b show estimated external force and wheel angular velocity. A force of about 100 N is sufficient to stop the vehicle, and it is confirmed that this force is equal to $V_0 b$.

When the same experiment is conducted for the switching algorithm shown in Fig.13, the wheel angular velocity is as shown in Figure 14. Compared to this, the wheel angular velocity shown in Figure 13b has less vibration and is better in light of smooth speed response does not surprise people.

7. Conclusion

In this research, in light of the issues related to the practicality of the unmanned driving function ”Smart Summon”, the application of impedance control to unmanned EVs is proposed with the aim of realizing a human-friendly interface for them. The effectiveness of the proposed method is confirmed by simulations and experiments. Thanks to the method, the possibility of realizing the interface that allows unmanned EVs and people to mix safely in places where cars and people come and go, such as parking lots.

In future research, it is desirable to confirm the effectiveness of the proposed method using sensory evaluation, and to study impedance models for more intuitive behavior for humans.

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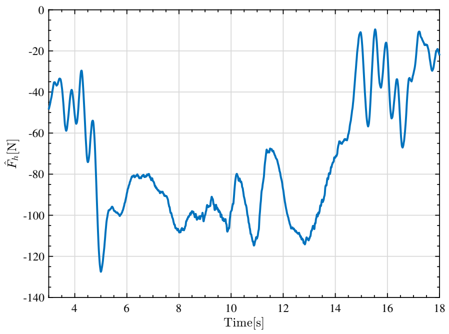
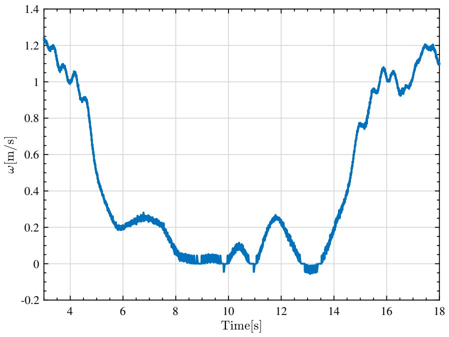


(a) $\hat{F}_h$



(b) ω

Figure 13: Experiment results of proposed method

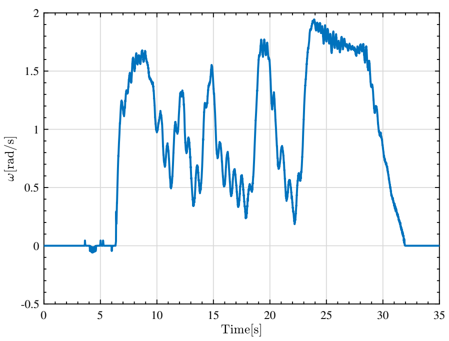


Figure 14: Experiment results of switching algorithm : ω

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