Electric vehicles (EVs) are gaining attention, and novel usages such as vehicle-to-home (V2H) are being proposed\(^{(1),(2)}\). In particular, in-wheel-motor (IWM) type EVs, which have four motors inside each wheel, are expected to be an ideal power train system because it can achieve precise driving force control and estimation. To exploit these features of IWM-EVs, researchers have proposed numerous control methods, most of which are velocity or position-based control for running or trajectory tracking. Force control technologies are quite popular in robotics divisions, and these methods are quite suitable for the new applications of EVs. By taking advantage of the precise estimation performance of IWM-EVs, the authors have proposed to apply force control to EVs and built the concept of human-friendly EVs as done in the robotics division. We show the external force estimation method using wheel resolvers and propose hand-assisted position adjustment method based on impedance control. The appropriate control structure is discussed for IWM-EVs, and its effectiveness is demonstrated with numerical simulations and experiments. We anticipate this research to generate many control applications suitable for the new application of cars.

**Keywords:** force control, electric vehicles, in-wheel-motor, impedance control, vehicle motion control

### 1. Introduction

As the concerns of environmental problems increases, Electric Vehicles (EVs) are getting attention, and novel usages such as vehicle-to-home (V2H) are being proposed\(^{(1),(2)}\). EVs are superior to internal combustion vehicles not only in the environmental aspect but also in controllability\(^{(3)}\). Especially, In-Wheel-Motor (IWM) type EV, which has drive motor inside each wheel, is expected as a next power train system\(^{(4)}\). IWM-EVs have many merits compared to conventional EV power train systems: the number of mechanical parts is reduced, a higher response is achieved, the driving force on each wheel can be estimated, and the driving force can be distributed within each of the four EV motors.

Numerous vehicle motion control methods have been proposed by taking advantage of IWM-EVs, (5) proposed lateral motion control robust for small torque variation, (6) proposed fault-tolerant trajectory tracking control for IWM-EVs, (7) optimal velocity trajectory generation method for range extension autonomous driving. Most of those control methods are designed to achieve higher performance or bring better stability for the driving, and most of them are position or velocity control in essence.

On the other hand, researches on “human-friendly robots” are familiar to the robotics division so that people and robots can work collaboratively. Not velocity or position control plays an essential roll in this research area, (8) proposed high-performance force control based on the bilateral control structure and analyzed its stability and performance, (9) achieved sensor-less impact force reduction control using aKF for printed circuit board test, and (10) adopts impedance control to reduce impact force. Force estimation technologies are also becoming more and more sophisticated, (11) realized FPGA based wide-band force control considering noise and friction. Contact point detection based on force sensing is also developed in (12).

Most of the force related applications for vehicles are about brake force or disturbance compensation. (13) proposed an antilock braking system based on nonlinear model predictive control. (14) developed an electric hydraulic braking actuator and achieved better braking performance with sliding mode control. (15) proposed combined slip ratio control using an antilock braking system and a torque generation of IWM. (16) proposed individual tire force estimation based on model switching. Lateral disturbance estimation and compensation are addressed in (17). (18) achieved efficient yaw moment control for IWM-EVs considering tire slip power loss. Some researches consider human-vehicle interaction using force control through electric power steering (EPS). (19) proposed a stable bilateral control system of EPS, and (20) uses impedance control to enhance operability. However, current researches do not focus on applying force control to the vehicle body.

On the other hand, mobility such as UAV introduces force control recently, (21) proposed IMU-based force estimation and proposed force control of UAV, which can interact with environments or human operators. (22) realized model predictive force control to “run” along with the wall.
Inspired by this trend, we have proposed force control for IWM-EV, which does not require any additional sensors and realized hand-assisted parking control \(^23\). As we have seen above, researches on force control are familiar to the industrial fields so that people and robots can collaborate. Since IWM-EVs can estimate external force, it is possible to apply numerous force control methods of robots for the IWM-EVs. Our contribution that we have launched the concept of “human-friendly” vehicle enables numerous applications such as “vehicles like a furniture” or “collision force reduction” that are possible \(^24\). Since new usages of EVs like V2H requires vehicles to be closer to people, this concept of the human-friendly vehicle is suitable for IWM-EVs.

In this paper, hand-assisted vehicle position alignment and its stability are discussed. Many people are not good at parking because position adjustment work is very different from the usual driving. This lack of driving skill sometimes leads to serious accidents. This method is convenient in situations that automatic parking cannot cope with, e.g., the valet parking or the case when the parking frame is not explicit. Our research group has proposed driving force control (DFC), which is a kind of a longitudinal tire force control method for IWM-EV \(^25\). By combining velocity impedance control \(^26\) and DFC, it has become possible to adjust vehicle position by human hand.

In this section, traction control method and impedance control performance of the proposals is verified in section 4.1 and section 5.1. Finally, the concluding remarks are in section 6.

2. Modeling of Vehicle Plant and Control Methods

The experimental vehicle and its physical model are shown in this section. Traction control method and impedance control based on minor velocity loop are also addressed.

2.1 Experimental Vehicle

Figure 1 shows the experimental setup and the concept of this research. The vehicle used in this study is FPEV2-Kanon, manufactured by our research group. Kanon has four outer-rotor type IWM, and each wheel can be independently controlled. In this research, rear wheels are used as a drive wheel for assist control. Since no reduction gears and no gear backlash are present in the units, the motors can drive the wheel directly.

2.2 Physical Model of Vehicle

In this paper, we assume the unicycle model where the same input torque is applied on each wheel. Figure 2 shows the vehicle model. Here, \( \omega \), \( V \), \( T \), \( F_d \), \( F_h \), represent wheel angular velocity, vehicle velocity, input torque, driving force, and external force from hand respectively. When the current control of the motor is fast enough, the motion equation of the wheel and vehicle body can be given as

\[
J\dot{\omega}_{ij} = T_{ij} - rF_{dij}, \quad \sum_{i,j} F_{dij} + F_h \quad \sum_{i,j} F_{dij} + F_h
\]

\( J, r, \) and \( M \) represent wheel inertia, wheel radius, and vehicle mass respectively. Here, driving resistance is ignored for simplicity. Subscript \( i \in (f, r) \) and \( j \in (l, r) \) respectively mean front-rear and left-right. Moreover, bold \( X \) four wheels means vector \( X = [X_{fl}, X_{fr}, X_{rl}, X_{rr}] \) of state variable \( X \) in the rest of this paper.

When the EV is accelerating, \( r\omega \geq V \) holds, and when decelerating, \( r\omega \leq V \) holds. In this paper, we assume the accelerating case and the slip ratio of wheels \( \lambda_{ij} \) is defined by

\[
\lambda_{ij} = \frac{r\omega_{ij} - V}{r\omega_{ij}}
\]

Wheel driving force \( F_{dij} \) can be calculated using friction coefficient \( \mu_{ij} \) and normal force \( N_{ij} \):

\[
F_{dij} = \mu_{ij}N_{ij}
\]

Typical relationship between slip ratio \( \lambda_{ij} \) and friction coefficient \( \mu_{ij} \) is shown on Fig. 3. Magic formula

\[
\mu_{ij}(\lambda_{ij}) = D \sin\left(C \tan^{-1} B(1 - E)\lambda_{ij} + \frac{E}{B} \tan^{-1} B\lambda_{ij}\right)
\]

Fig. 1. Experimental vehicle: FPEV2-kanon

Fig. 2. Vehicle physical model

Fig. 3. \( \mu - \lambda \) curve
is the well-known approximate expression of this relation, where B, C, D and E are non-dimensional constants, usually determined according to fitting.

When the slip ratio is small enough, \( F_{dij} \) can be expressed as a linear system

\[
\mu_{ij} = \frac{D_s \lambda_{ij}}{N_{ij}}, \hspace{1cm} (6)
\]

\( D_s \) is a variable called driving stiffness. Figure 4 depicts the block diagram of the vehicle model.

### 2.3 Control Methods

#### 2.3.1 Driving Force Control

Our research group has proposed DFC in (25), which can control the driving force \( F_{dij} \) between the road and the wheels while avoiding wheel slip. DFC is composed of an outer loop controlling \( F_{dij} \), an inner wheel speed control loop, and a reference generation part preventing wheel slip.

Driving force observer (DFO) is used to estimate forces between wheels and road \( F_d \). DFO estimates \( F_d \) based on

\[
F_{dij} = \frac{1}{1 + \tau_{s} \delta} \left( T_{ij} - J \omega_{ij} \right), \hspace{1cm} (7)
\]

Outer-loop feeds back this estimated driving force.

Friction coefficient reaches a maximal value at some \( \lambda_{\text{peak}} \) and decreases when \( \lambda \) is larger than \( \lambda_{\text{peak}} \) as shown on Fig. 3. Therefore, the DFC system involves a slip ratio controller to prevent the wheel slip. As shown on (6), \( \lambda \) to \( F_d \) is the zero order plant. Therefore, PI controller \( C_{\nu}(s) = K_p v + \frac{K_i}{s} \) is used to achieve slip ratio control. By limiting the output of the I controller \( C_{\nu}(s) = \frac{k_i}{s} \), the slip ratio falls within the desired range and tire slipping can be prevented.

#### 2.3.2 Impedance Control

Impedance control is kind of a force control that can change mechanical impedance between robot and environment, such as stiffness, damping constant, or mass. This control method is often used to implement assistance control or impact force reduction.

Impedance control has numerous variations, and here we address the velocity control based system. Figure 5 shows the typical impedance control system based on velocity control. Velocity reference is calculated from the contact force and model impedance. Robot velocity is controlled so that the end effector emulates the model impedance. In Fig. 5, external contact forces are estimated by disturbance observer.

### 3. Proposal of EV Hand-assisted Control

Here, we propose to apply impedance control to IWM-EVs. In this section, how to apply impedance control to IWM-EV is discussed, and three structures are suggested.

#### 3.1 External Force Estimation Method

An external force from a human hand can be estimated with a reaction force observer (RFOB).

From equation (1) and (2), RFOB to estimate \( \hat{F}_h \) can be expressed as

\[
\hat{F}_h = \frac{1}{1 + \tau_{b}s} \left[ sMV - \frac{1}{r} \sum_{i,j} \left( T_{ij} - sJ \omega_{ij} \right) \right]. \hspace{1cm} (8)
\]

This estimation method estimates external force based on driving force of each wheel obtained by DFO as shown on Fig. 7(b). This structure is similar to the multi-encoder based disturbance observer in (27).

The angular velocity is acquired by differentiating the sensor value of the wheel resolvers, and the quantization noise expands through the differentiation and estimation process. This estimation method has more noise compared to the single typical encoder based disturbance observer while the low-resolution resolvers are often used as a wheel angle sensor.

Therefore, to reduce noise, we propose another estimation method. By removing \( F_d \) from (1)–(2),

\[
M \ddot{V} - \frac{1}{r} \sum_{i,j} \left( J \omega_{ij} - T_{ij} \right) = F_h \hspace{1cm} (9)
\]

can be obtained. Since the vehicle speed is low in this system and only translational motion is considered here, nonholonomic constraints of \( \lambda_{ij} = 0 \) and \( V = \frac{1}{r} \sum_{i,j} \omega_{ij} \) hold. Therefore, the estimation formula considering the nonholonomic constraint

\[
\hat{F}_h = \frac{1}{1 + \tau_{b}s} \sum_{i,j} \frac{1}{r} \left[ \left( J + \frac{r^2}{4} M \right) \omega_{ij} - T_{ij} \right]. \hspace{1cm} (10)
\]

is obtained. In this estimation method, the vehicle body and wheel plant are regarded as one, and the slip ratio is assumed to be 0. The single DOB method is robust against quantization noise and appropriate for wheel resolver, whose resolution is not high. However, this method cannot separate the effect of road surface change from \( F_h \) and approximation effects as a modeling error. The fact that \( F_h \) contains the effect of road surface change and travel resistance should be noted.

#### 3.2 Control System Design of EV Hand-assisted Control

Here, we discuss how to apply impedance control to
the IWM-EVs. By designating smaller model impedance $m$, we can realize hand-assisted position adjustment. We should consider the structure of the speed controller to apply velocity based impedance control for the vehicles.

The most straightforward idea is just putting the velocity loop outside each motor torque control loop. The other idea is to embed DFC as a minor loop. Expression (2) implies robustness against road disturbance enhances by controlling $F_d$. Since the driving force does saturate due to slip, slip ratio reference generation is not necessary for the hand-assisted control.

Since $F_h$ means external force from human hands, a high response is not required for the velocity control loop. From (2), the PI controller $C_V = K_p V + K_i V$ is adopted for vehicle velocity control to track the lamp reference. Moreover, since the velocity of EV is limited to the low-speed region in the hand-assisted position control, the wheel slip is tiny.

Figure 6 shows this block diagram with minor DFC with driving force control with DFC. The necessity of the DFC is discussed in the next section.

### 3.3 Organization of the Control Strategies

By incorporating the outer velocity loop and $F_h$ estimation, it becomes possible to apply impedance control to IWM-EV. However, we have two things to be discussed here: (1) The necessity of DFC, which seems to improve robustness against the road disturbance. (2) Feasibility of proposed estimation methods under the existence of quantization noise. To discuss those problems, we have prepared three choices, which are shown on Table 1, as a structure of impedance control for IWM-EV. Those 3 cases are compared through numerical simulations in the following section.

### 4. Numerical Simulation and Analysis

In this section, we discuss which of the case 1~3 is adequate with numerical simulations. Stability of the proposed method is also addressed.

#### 4.1 Simulation Condition

The simulation parameters are shown on Table 2. Every 3 cases are simulated and compared. In the simulation, external force working on the EV plant is a low-pass-filtered 200 N step signal which emulates the force from the human hand. The vehicle body is controlled so that the total mass would become 200 kg even though the actual mass of EV body is 854 kg. The cutoff
frequency of DFO is decided based on (25), and we have confirmed the cutoff frequency of 30 rad/s is high enough and does not harm the quality of estimation in the preliminary experiment using force sensor. Controllers are designed with the pole placement of the jack-upped vehicle model. Poles of driving force controllers are placed on 8 rad/s, and those of vehicle speed controllers are placed on 3 rad/s. Since the driving force is not controlled in case 2, only the speed controller poles are allocated.

4.2 Simulations in Ideal Situation

Figure 8 is the simulation result of case 1∼3, which shows the estimated external force and vehicle speed. $F_h$ is estimated correctly in all figures. The blue and red lines of Fig. 8 respectively mean the vehicle speed with and without control. Although the same forces are applied, the vehicle travels faster than no assistant control case, and the intended control is achieved appropriately. The black line shows the velocity of the ideal vehicle whose mass is 200 kg, which is model impedance. The blue line overlaps the black line, meaning that the vehicle speed is controlled as if the EV mass becomes 200 kg.

4.3 Effect of Quantization Error

The estimation method (8) generates larger quantization noise compared to (10), which leads to decline of control performance. Then, we conducted the simulation with a resolver quantization error to compare the quantization noise of 2 estimation methods. The resolution of the wheel resolver is 12 bit, which is the same as the actual experimental vehicle. The cutoff frequencies of case 1 are set to 8 rad/s, and that of case 3 is decided so that the noise ripple of both methods become the same order.

Figure 9 shows the estimated $F_h$. Each black, red, blue line means true $F_h$, cases 1 and 3. To achieve the same estimation accuracy, the cutoff frequency of case 3 needs to be set on 2 rad/s, which is four times lower than that of case 1. When encoder resolution is not high enough, we should use (10) as an estimation method to ensure control bandwidth.

4.4 Control Loop Design and Road Disturbance

By comparing cases 1 and 2 on simulations, the necessity of DFC is discussed. In addition to above conditions, road surface change is reflected in these simulations. The friction coefficient of the road $\mu$ is reduced from 0.8 to 0.2 at 4 sec, and its effect is checked.

The simulation results of case 1 and 2 are respectively shown on Figure 10. Though the road surface condition affects $F_h$ estimation, case 1 works well. On the other hand, in case 2, $F_h$ does not converge to the actual value, and the assist control system diverges from reference. This result demonstrates the necessity of minor DFC to achieve hand-assisted position alignment control of IWM-EVs.

4.5 Stability Analysis

The simulation results suggest that case 1 is the most appropriate structure to apply impedance control for IWM-EVs. Here, we discuss the stability of case 1. To analyze the stability of the proposed control method, we should conduct linearization around an operating point because the vehicle plant has two nonlinearity: $\mu - \lambda$ curve and (3). Since the slip is small enough in the proposed method, this linearization is appropriate. $\mu - \lambda$ curve
is linearized as a driving stiffness, and (3) is linearized based on reference paper (28). A linearized plant can be expressed as

\[
\Delta \lambda \Delta T = \frac{1 - \lambda_0}{J \omega_0 s + \frac{D_s}{J r M}(J + r^2 M(1 - \lambda_0))}, \quad \cdots \cdots \quad (11)
\]

\[
\Delta V \Delta T = \frac{D_s}{M J \omega_0 s^2 + \frac{D_s}{J r M}(J + r^2 M(1 - \lambda_0))s}, \quad \cdots \cdots \quad (12)
\]

\[
\Delta \omega \Delta T = \frac{J \omega_0 s + \frac{D_s}{J r M}(J + r^2 M(1 - \lambda_0))}{J \omega_0 s + \frac{D_s}{J r M}(J + r^2 M(1 - \lambda_0))}, \quad \cdots \cdots \quad (13)
\]

These linearized model also implies the necessity of DFC from the viewpoint of colocate and phase delay.

With those linearized plant model, the characteristic equation of the closed-loop system is given by

\[
a_0 s^4 + a_1 s^3 + a_2 s^2 + a_3 s + a_4 = 0, \quad \cdots \cdots \quad (14)
\]

where

\[
a_0 = J M r \omega_0;
\]

\[
a_1 = D_s(J + D_s M r^2 - M \lambda_0 r^2 + K_{pF}\omega_0 M - K_{pF} M \lambda_0 r);
\]

\[
a_2 = r D_s(K_{pF} K_{pF} + K_{pF} K_{pF} - K_{pF} K_{pF} \lambda_0 - K_{pF} K_{pF} \lambda_0);
\]

\[
a_3 = r D_s(K_{pF} K_{pF} + K_{pF} K_{pF} - K_{pF} K_{pF} \lambda_0 - K_{pF} K_{pF} \lambda_0);
\]

\[
a_4 = r D_s(K_{pF} K_{pF} - K_{pF} K_{pF} \lambda_0).
\]

Since driving phase is assumed, Routh’s criterion follows

\[
r(K_{pF} K_{pF} + K_{pF} K_{pF})(1 - \lambda_0)(D_s r(K_{pF} K_{pF} + K_{pF} M) (J + M r^2 + K_{pF} M r - M \lambda_0 r^2 - K_{pF} M \lambda_0 r) > D_s K_{pF} K_{pF} r(J + M r^2 + K_{pF} M r - M \lambda_0 r^2 - K_{pF} M \lambda_0 r^2) \cdot \cdots \cdots \quad (15)
\]

Since driving phase is assumed, Routh’s criterion follows

\[
r(K_{pF} K_{pF} + K_{pF} K_{pF})(1 - \lambda_0)(D_s r(K_{pF} K_{pF} + K_{pF} M) (J + M r^2 + K_{pF} M r - M \lambda_0 r^2 - K_{pF} M \lambda_0 r) > D_s K_{pF} K_{pF} r(J + M r^2 + K_{pF} M r - M \lambda_0 r^2 - K_{pF} M \lambda_0 r^2) \cdot \cdots \cdots \quad (15)
\]
Velocity and driving force controller should be determined within this criterion.

5. Experiment

5.1 Experimental Conditions

For the experiment, case 1 is adopted as a control strategy. The proposed method is compared with the case without any assist. In the experiment, the rear wheels are used for the assist control front wheels are used to emulate the external force from the human hands. Low-pass-filtered step 200 N torque reference is applied on front wheels. Since the slip is small enough, the average of the wheel velocities is used to calculate vehicle speed \( V \). Control and estimation parameters are the same as the simulation.

5.2 Experimental Results

Figure 11 shows the experimental result. The blue line in the Fig. 11(a) shows the \( F_\delta \) smoothed with a low pass filter whose filter constant is 3 rad/s, and the black line shows the driving force of the front wheels. Though the estimated force contains the road disturbance and the mechanical losses, it is value transitions around the actual value. Figure 11(b) shows the vehicle speed with and without control. The experimental result similar to the simulation result is obtained, and thus the assist control is achieved.

To validate the control performance of the proposed method, we conducted the same experiment 10 times. When the assistance control is applied, the average acceleration in 5 sec is 0.3961 m/s\(^2\), which is 4.22 times larger than the case without any assistance control. This value almost corresponds with 4.4 = 880/200.

Vehicle velocity in Fig. 11(b) is slower than Fig. 8. The experimental vehicle speed at 5 sec is only 1/3 of simulation. Rolling frictions, travel resistance, and starting torque, which is not considered in the simulations, are the main reasons.

6. Conclusion

In this research, force control for IWM-EV is proposed using impedance control. Its control system is discussed from the viewpoint of estimation and control loop. The best one is chosen from some control strategy, and its feasibility is analyzed by simulations. With an experiment, we have demonstrated it works well with actual vehicles. Thanks to this proposed method, the mechanical impedance of EVs can be arbitrarily chosen, and the concept of human-friendly EV is achieved. Numerous applications would be proposed based on this concept of force control of vehicles.

Acknowledgment

This research was partly supported by the Industrial Technology Research Grant Program from the New Energy and Industrial Technology Development Organization (NEDO) of Japan (number 05A48701d), the Ministry of Education, Culture, Sports, Science, and Technology grant (number 22246057 and 26249061). This study was partly supported by JSPS KAKENHI Grant Number 18J14169.

References


(22) K. Alexis, C. Huerzeler, and R. Siegwart: “Hybrid Modeling and Control of a Coaxial Unmannmed Rotocraft Interacting with its Environment through Contact”, in IEEE International Conference on Robotics and Automation,
Tomoki Emmei (Student Member) received the B.S. and M.S. degrees from the University of Tokyo in 2015 and 2017, respectively. He is currently working as a Ph.D. degree in the Department of Electrical Engineering and Information Systems, the University of Tokyo, Japan. He is also a research fellow of the Japan Society for the Promotion of Science from 2018(JSPS-DC2). He received the IEEJ Young Researcher’s Award in 2015 and the Dean’s Award for Outstanding Achievement from the Graduate School of Frontier Sciences and Faculty of Engineering, the University of Tokyo in 2017 and 2015 respectively. His interest includes motion control and electric vehicle control. He is a student member of the Institute of Electrical and Electronics Engineers.

Hiroshi Fujimoto (Senior Member) received the Ph.D. degree in the Department of Electrical Engineering from the University of Tokyo in 2001. In 2001, he joined the Department of Electrical Engineering, Nagaoka University of Technology, Niigata, Japan, as a research associate. From 2002 to 2003, he was a visiting scholar in the School of Mechanical Engineering, Purdue University, U.S.A. In 2004, he joined the Department of Electrical and Computer Engineering, Yokohama National University, Yokohama, Japan, as a lecturer and he became an associate professor in 2005. He is currently an associate professor at the University of Tokyo since 2010. He received the Best Paper Awards from the IEEE Transactions on Industrial Electronics in 2001 and 2013, Isao Takahashi Power Electronics Award in 2010, Best Author Prize of SICE in 2010, the Nagamori Grand Award in 2016, and First Prize Paper Award IEEE Transactions on Power Electronics in 2016. His interests are in control engineering, motion control, nano-scale servo systems, electric vehicle control, motor drive, visual servoing, and wireless motors. He is a senior member of IEE of Japan and IEEE. He is also a member of the Society of Instrument and Control Engineers, the Robotics Society of Japan, and the Society of Automotive Engineers of Japan. He is an associate editor of IEEE/ASME Transactions on Mechatronics from 2010 to 2014, IEEE Industrial Electronics Magazine from 2006, IEE of Japan Transactions on Industrial Application from 2013, and Transactions on SICE from 2013 to 2016. He is a chairperson of JSAE vehicle electrification committee from 2014 and a past chairperson of IEEE/IES Technical Committee on Motion Control from 2012 to 2013.