

# 4 Wheel Motored Vehicle "UOT Electric March II" -Experimental EV for Novel Motion Control Studies-

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## KEYWORDS

Electric vehicles, Motion Control, Anti-lock Braking System, Direct Yaw Moment Control.

## ABSTRACT

"UOT(University of Tokyo) Electric March-II" is our novel experimental EV. It is 4-wheel motored EV: every wheel has its own driving motor. Each motor can be fully driven independently. This EV is for intensive studies of "motion control of electric vehicle", since it will be an important research issues. EV has great advantage on control performance: fast and accurate motor torque generation. Therefore, advanced methods can be applied for wheel skid prevention or road condition estimation. With small motors like in-wheel motors, even the lateral motion control is available. This paper first introduces "UOT Electric March II", then describes such research topics which were and will be demonstrated with our new EV.

## 1 INTRODUCTION

Recently, electric vehicles (EVs) are intensively developed. With improvement of motors and batteries, some pure EVs (PEVs) with only secondary batteries have already achieved enough performance. Hybrid EVs (HEVs), like Toyota Prius, are going up to the commercial products. Fuel cell EVs (FCEVs) will possibly be major vehicles in this 21<sup>st</sup> century. The background of this developments is energy and environmental problems, thus main concern over EVs is energy efficiency and environmental impacts. However, another important advantage exists, which is not recognized well yet. It is controllability of electric motors.

From the viewpoint of electrical and control engineering, EVs have evident advantages over internal combustion engine vehicles (ICVs). These advantages can be summarized as:

1. ***Torque generation of electric motor is very quick and accurate, for both accelerating and decelerating.***

This should be the essential advantage. ABS (antilock brake system) and TCS (traction control system) should be integrated into "total TCS", since a motor can both accelerate or decelerate the wheel. Its performance should be advanced one, if we can fully utilize the fast torque response of motor [1].

## 2. Motor torque is easily comprehensible.

There exists little uncertainty in driving or braking torque inputted by motor, compared to that of combustion engine or hydraulic brake. Therefore, simple “driving force observer” can achieve a real-time observation of driving/braking force between the tire and road surface [2] [3]. This second advantage will contribute a great deal to several applications like road condition estimation.

## 3. Motor can be attached to each wheel.

With small motors like in-wheel motors (Fig. 1), even the anti-directional torque generation is possible on left and right wheels. In automobile engineering, such approach is known as *DYC* (direct yaw moment control) [4] [5]. Distributed motor will possibly enhance its performance.

Definitely, these indicate the novel approach for vehicle motion control in EVs. Automobile engineers recently assume that active vehicle control is the important technique. It is directly connected with safety, or human life. We, electric engineers, will be able to contribute a lot to this novel and important theme: advanced motion control of EVs.

“UOT Electric March II” is a novel experimental EV, which has been constructed for these studies in 2001. It is 4 wheel motored EV: every wheel has its own driving motor(Fig. 1). Computers for motion control, sensors like fiber-gyro type yaw rate sensor, and inverter units which generates the commanded torque are also equipped. Thus it is an ideal vehicle for both longitudinal and lateral motion studies.

In the following parts, section 2 introduces this laboratory-made EV. Subsequent sections mention the research topics which this EV is constructed for. Feedback based approach with fast motor response is our basic strategies(Fig. 2). Such minor controller can change the plant dynamics and enhance the stability on slippery road surface. Longitudinal stability is discussed in section 3, and section 4 concerns the lateral motion stability enhancement with this minor controller. Lateral stability is studied not only with simulations, but also experimental results with “UOT Electric March II.” Other research issues, which are planed to be demonstrated with this EV, are shortly introduced in section 5. Section 6 concludes this paper.

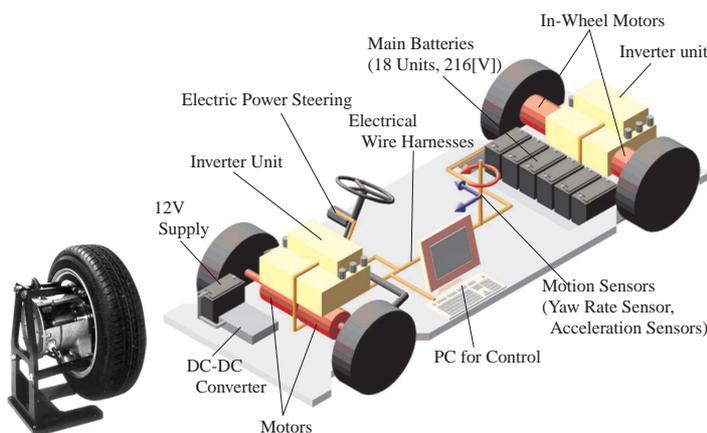


Figure 1: In-wheel motor (left) and our new EV with four in-wheel motors. (right)

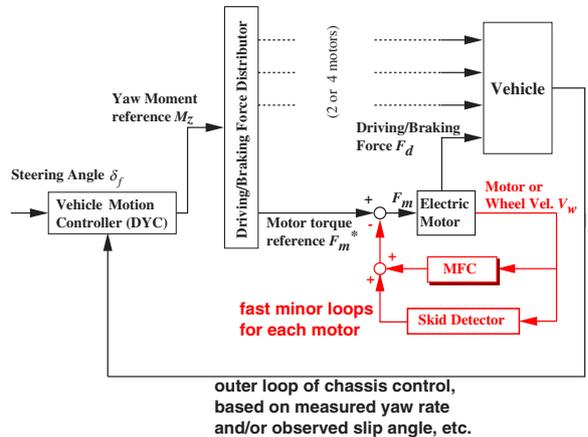


Figure 2: Our basic idea: total system with minor feedback loops

## 2 EXPERIMENTAL EV “UOT ELECTRIC MARCH II”

“UOT Electric March II” is our novel EV for experimental discussions. This EV can be characterized by its original motor configuration: 4 independent motors. Each wheel has their own driving motor, therefore, driven wheels can be independently controlled. Regenerative braking is also available in this vehicle. We ourselves designed and built up this vehicle, based on the conventional ICV “Nissan March”.

The specification of this EV focuses on the motion control experiments. It has adequate devices for experiments: on-board PCs and several sensors like fiber-optic gyro. Motion controller constructed in the PC outputs the torque commands, and inverter units generate the torques of these values. This precise torque generation is achieved by motor current controller in the inverter unit. On the other hand, the distance for one-charge, energy efficiency, driving comfort or other features are excluded from discussions. Table 1 summarizes the key specifications of “UOT Electric March II”.



Figure 3: “UOT Electric March II” running at about 100 [km/h].

Table 1: Spec. of “UOT Electric March II”.

<b>Drivetrain</b>	<b>4 PM Motors</b>
Max. Power(20 sec.)	36 [kW] (48.3[HP])*
Max. Torque	77* [Nm]
Gear Ratio	5.0
<b>Battery</b>	<b>Lead Acid</b>
Weight	14.0 [kg](for 1 unit)
Total Voltage	228 [V] (with 19 units)
<b>Base Chassis</b>	<b>Nissan March K11</b>
Wheel Base	2360 [m]
Wheel Tread F/R	1365/1325 [m]
Total Weight	1400 [kg]
Wheel Inertia**	8.2 [kg]**
Wheel Radius	0.28 [m]
<b>Controller</b>	
CPU	MMX Pentium 233[MHz]
Rotary Encoder	3600 [ppr]**
Gyro Sensor	Fiber Optical Type

\* ... for only one motor.

\*\* ... mass equivalent.

\*\*\* ... affected by gear ratio.



Figure 4: Photo of turning experiments with 4W-motored EV “UOT Electric March II” (Fig. 12-13).

### 3 WHEEL VELOCITY CONTROLLER FOR SKID PREVENTION

In this section, the wheel velocity controller for skid prevention is discussed. The starting point of this idea is to utilize the knowledge on motion control, which is based on the motor control. In general, the feedback controller can change the dynamics of plant, or we can re-design the plant dynamics. For example, the plant can be insensitive against disturbance if appropriate feedback controller is applied. Such feedback controller requires fast response of actuator, and it is available in EVs. So, how we should design the controller or plant dynamics for skid prevention? This is the main topics in this section.

#### 3.1 SLIP PHENOMENA AND LINEAR SLIP MODEL

Ordinary, slip ratio  $\lambda$  is used to evaluate the “slip”. Slip ratio  $\lambda$  is defined as,

$$\lambda = \begin{cases} \frac{V_w - V}{V_w} & : \text{for accelerating wheel,} \\ \frac{V_w - V}{V} & : \text{for decelerating wheel,} \end{cases} \quad (1)$$

where  $V$  is the vehicle chassis velocity.  $V_w$  is the velocity equivalent value of wheel velocity,  $V_w = r\omega$ , where  $r$ ,  $\omega$  are the wheel radius and wheel rotating velocity, respectively.

With simple one wheel model (Fig. 5), the motion equations of wheel and chassis can be obtained as

$$M_w \frac{dV_w}{dt} = F_m - F_d(\lambda), \quad (2)$$

$$M \frac{dV}{dt} = F_d(\lambda), \quad (3)$$

if air resistance on chassis and rotating resistance on wheel are both negligible.  $M$  and  $M_w$  are the vehicle weight and the mass equivalent value of wheel inertia, respectively.  $F_m$  is the force equivalent value of accelerating/decelerating torque, generated by engine, hydraulic brake system or motor.  $F_d$  is the driving/braking force between the wheel and the road surface. This  $F_d$  has nonlinear dependence on the slip ratio  $\lambda$ , such as in Fig. 6<sup>1</sup>.

For the controller design process, linear skid model is derived from (1)-(3) and  $F_d(\lambda)$  in Fig. 6. Nonlinearity exists in  $F_d(\lambda)$  or  $\mu - \lambda$  curve, therefore, perturbation equation for  $F_d(\lambda)$ ,

$$\Delta F_d = N \Delta \mu = N a \Delta \lambda \quad (4)$$

$$= -\frac{1}{V_{w0}} \Delta V + \frac{V_0}{V_{w0}^2} \Delta V_w \quad (5)$$

is used here. The parameter  $a$  is the gradient of  $\mu - \lambda$  curve,

$$a = \left. \frac{\partial \mu}{\partial \lambda} \right|_{(V_0, V_{w0})}. \quad (6)$$

$V_{w0}$ ,  $V_0$  are the wheel velocity and chassis velocity at the operational point, respectively. With (1)-(3) and (5), the transfer function from motor torque  $F_m$  to the wheel velocity  $V_w$  is

$$P(s) = \frac{\Delta V_w}{\Delta F_m} = \frac{1}{(M_w + M(1 - \lambda_0))s} \frac{\tau_w s + 1}{\tau_a s + 1}, \quad (7)$$

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<sup>1</sup> $\mu = F_d/N$ , where  $N$  is the normal force on the wheel.

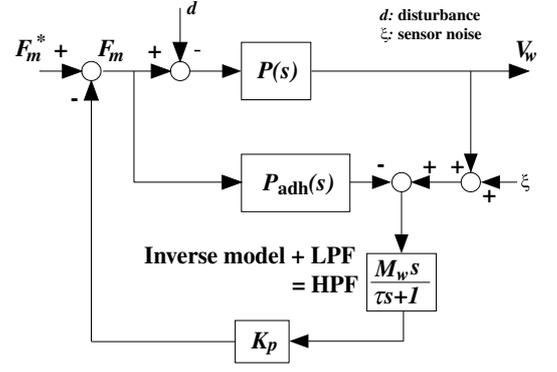
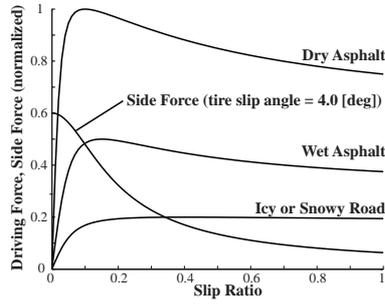
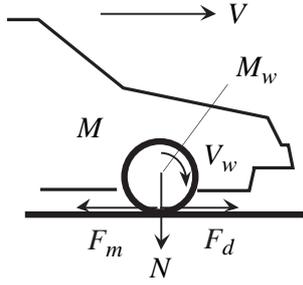


Figure 5: One wheel model. Figure 6: Typical  $\mu-\lambda$  curve. Figure 7: Proposed feedback controller.

where

$$\tau_a = \frac{M_w V_{w0}}{aN} \frac{M}{M(1 - \lambda_0) + M_w}, \quad \tau_w = \frac{M V_{w0}}{aN}. \quad (8)$$

$\lambda_0$  is a slip ratio at the same operational point ( $V_0, V_{w0}$ ).

From (7)-(8), the most simple models  $P_{adh}(s)$  (for adhesive wheel) and  $P_{skid}(s)$  (for completely skidding wheel) are

$$P_{adh}(s) = \frac{1}{M + M_w} \frac{1}{s}, \quad P_{skid}(s) = \frac{1}{M_w} \frac{1}{s}. \quad (9)$$

### 3.2 CONTROLLER DESIGN

Therefore, One dominant phenomenon in the wheel skidding is the rapid change of wheel rotating velocity. With wheel skidding during the acceleration, the wheel velocity rapidly increases, and during the deceleration it rapidly drops due to the wheel lock. Eq. (9) describe that sudden drop of wheel equivalent inertia causes this rapid change of wheel velocity. Based on this viewpoint, we design the feedback controller of Fig. 7 [1]. This controller can suppress such sudden drop of inertia as shown in Fig. 8.

Fig. 8 is the bode diagram of  $V_w/F_m^*$ . Left graph plots  $V_w/F_m^*$  for wheel without controller, i.e., plots  $P_{adh}(s)$  and  $P_{skid}(s)$ . If the controller of Fig. 7 is applied, these transfer functions are changed into the ones in the right graph. These figures clearly indicate that the dynamics of skidding wheel comes to be almost same as that of adhesive wheel, the “heavy” wheel. The wheel with proposed controller is insensitive for slip phenomena.

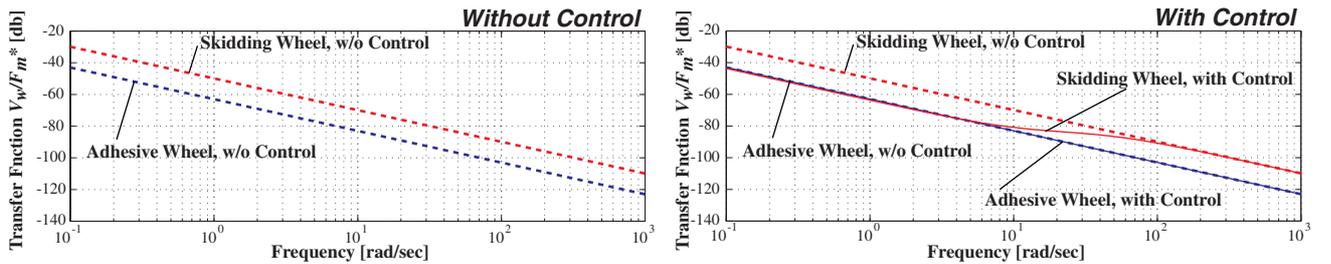


Figure 8: Bode diagram of  $V_w/F_m^*$ .  $K_p = K_p^* = \frac{M+M_w}{M_w}$ .  $\tau = 0.1[sec]$ .

### 3.3 EXPERIMENTAL RESULTS

Experiments were carried out to confirm the proposed method. These experiments were carried out with “UOT Electric March-I”, which is our another laboratory-made EV (Fig. 9) constructed in 1997 [1]. To examine the effect of wheel velocity control for skid avoidance, slippery low  $\mu$  road is required. We put the aluminum plates of 14[m] length on the asphalt, and spread water on these plates. The peak  $\mu$  of this test road is about 0.5. This value was estimated based on some other experimental results [3].

Fig. 10 shows the time responses of slip ratio. In these experiments, vehicle accelerated on the slippery test road, with lineally increasing motor torque. Without control, the slip ratio rapidly increases. On the contrary, the increase of slip ratio is relatively slow with proposed controller. As mentioned above, the wheel equivalent inertia during the wheel skidding comes to be “heavy” with wheel velocity control, thus the rapid increase of slip ratio can be suppressed.

Note that this method cannot be a complete skid prevention controller by itself. Proposed controller suppressed the rapid growth of slip ratio, however, the slip ratio finally exceeded the stable limit (Fig. 10). Therefore, we suggest this method as a minor-loop controller, to improve other method like conventional ABS or skid detection technique with EV [7].

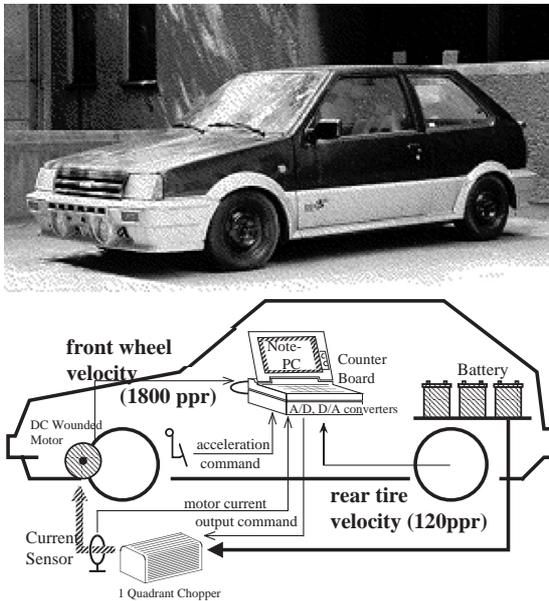


Figure 9: “UOT Electric March-I”.

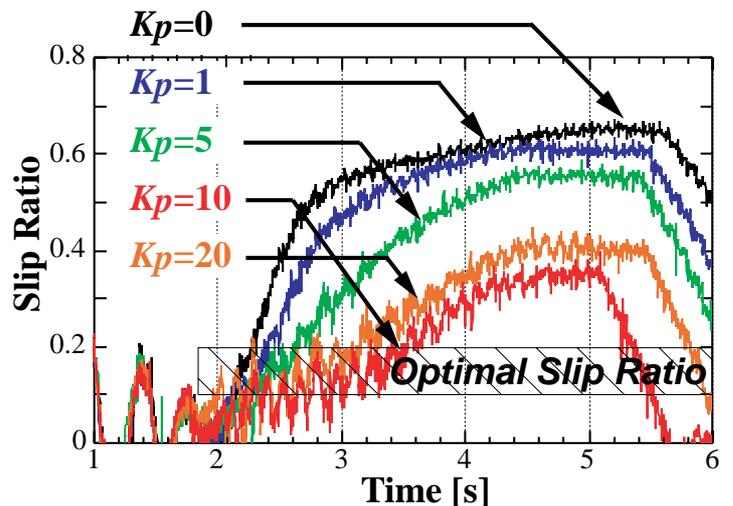


Figure 10: Effect of wheel velocity control for skid prevention with  $\tau=0.1$ [s] (Experimental results.)  $K_p^*$  is 4.52 for this vehicle.

## 4 LATERAL MOTION STABILIZATION WITH MOTOR CONTROL

### 4.1 CONCEPT AND SIMULATION STUDIES

In the previous section, wheel velocity feedback method was discussed. With this method, wheel equivalently has heavy inertia during slip. This suppresses the rapid increase of slip ratio. Then, what will happen if we apply such feedback loop for every wheel of turning vehicle on slippery road ?

As commonly known, the vehicle lateral motion can be sometimes unstable. This instability occurs in such situation as rapid braking during the turning, especially with slippery road

condition with snowy or rainy weather. Here we assume that one small motor is attached on every wheel of target EV. In-wheel motor is a typical example (Fig. 1). With such motors, the wheel velocities can be controlled independently. Our simulation results (Fig. 11) show that this minor loops can enhance the vehicle’s lateral stability [6]. Chassis’s 3-DOF nonlinear motion, four wheel’s rotation and dynamic load distribution are calculated in these simulations.

In these simulations, the vehicle starts running on the slippery road ( $\mu_{\text{peak}} = 0.5$ ), turning left with steering angle  $\delta_f = 3$  [deg]. Then at 5.0 [sec], the driver inputs rapid braking torque  $F_m = -1100$ [N] on each wheel. This torque exceeds the tire performance. Therefore, the wheel skid occurs and the chassis starts the spin motion, although the driver stops braking at 9.0 [s]. This wheel skidding is serious at rear-left wheel especially, since the center-of-gravity is shifted and the load distribution varied.

On the contrary, if the wheel velocity controller is applied independently for each wheel, such dangerous spin motion is prevented. The rear-left wheel’s torque is most reduced automatically. Note that this method uses only wheel velocities as feedback signals, therefore, differs considerably from conventional methods like DYC [4] [8]. The autonomous stabilization of each wheel, which is achieved with wheel velocity feedback, enhances the stability of vehicle lateral motion on slippery road. This effect is demonstrated in the next subsection.

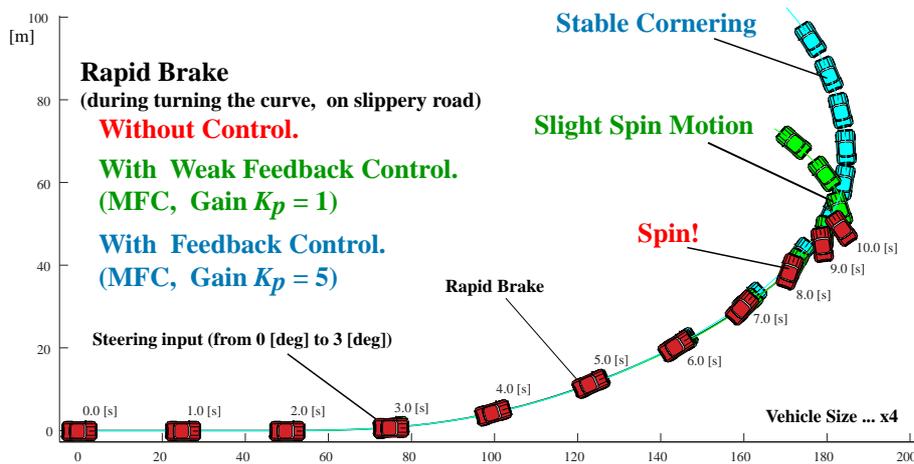


Figure 11: Stabilizing effect with “controlled four wheels” is visualized with vehicle’s trajectory [6].

## 4.2 BASIC EXPERIMENTAL RESULTS WITH “UOT ELECTRIC MARCH II”

Then the results of first experiments using “UOT Electric March II” is introduced here. In these experiments, “UOT Electric March II” was turning on the slippery test road, so-called skid pad (Fig. 4). At first, it was making steady turning in the clockwise direction. Turning radius and chassis velocity were about 25-30 [m] and 40[km/h], respectively. These values were closed to the unstable region. At 0 [s], acceleration torque of 1000 [N] was applied for rear two motors. Without any feedback control, this excessive acceleration causes the unstable vehicle motion. Fig. 12 shows this unstable vehicle motion <sup>2</sup>. The rear-right or rear-inside wheel started skidding seriously. Then yaw rate  $\gamma$  unstably grew as shown in the upper-right graph of Fig. 12. It indicates the spin motion. Vehicle was completely out of control and at 2[sec], experiment was terminated for safety reasons.

On the contrary, such dangerous motion could be prevented with minor feedback of wheel velocity. Fig. 13 and Fig. 14 shows this effect clearly. Note that controllers on rear-left and

<sup>2</sup>Chassis velocities in Figs. 12 and 13 are the mean values of trailing front wheels.

rear-right wheels are the same and independent ones. Each controller only requires the value of each wheel's velocity, thus it is not "connected" with each other in any meanings. Consequently, it can be said that autonomous stabilization of each driven wheel was achieved, and it enhanced the vehicle lateral stability. This indicates the validity of simulations in the previous section.

One of the remaining problems is the high-frequency oscillation induced at the rear wheels. We suppose that it depends on the design of controller. The cut-off frequency  $\tau$  in the proposed controller (Fig. 7) may have the important influence on this oscillation, however, such discussions must wait for the next experiments.

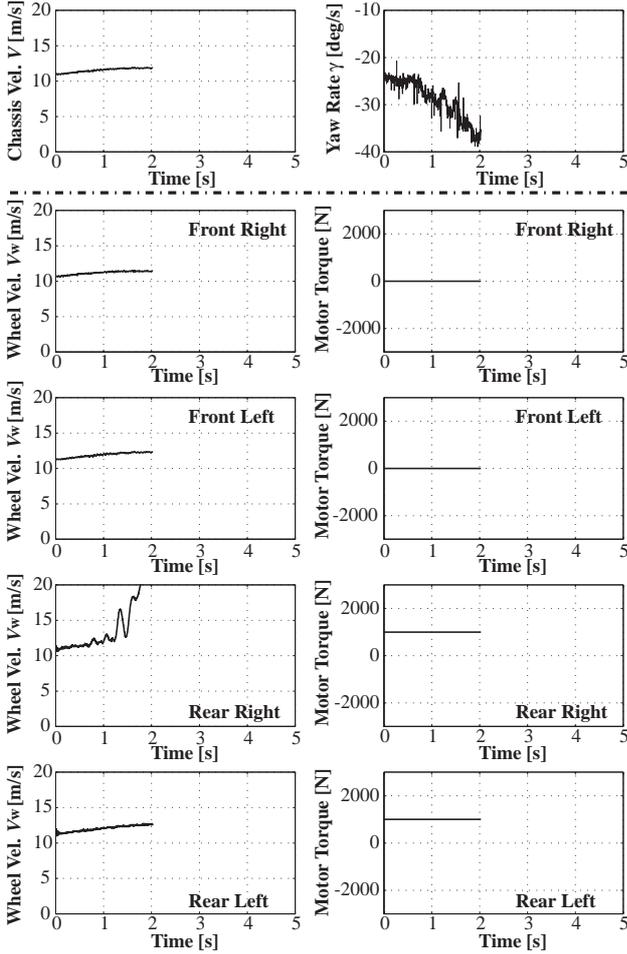


Figure 12: Unstable turning with sudden acceleration torque on rear wheels. Vehicle made steady turning before torque inputs.

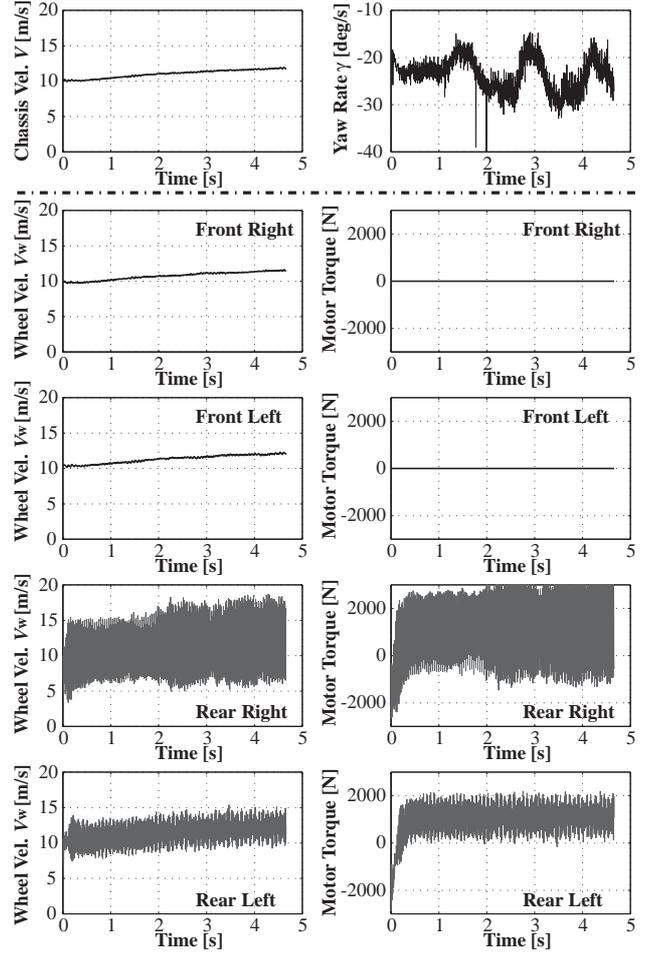


Figure 13: Stabilizing effect of wheel velocity feedback. Proposed controller of Fig. 7 was applied on both rear wheels.

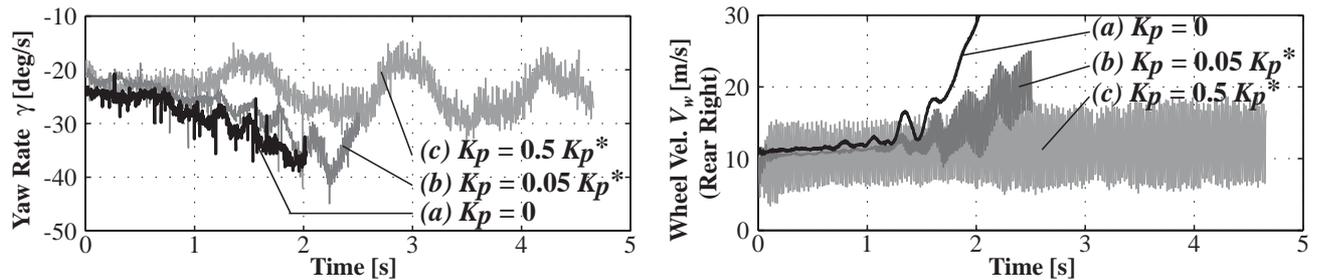


Figure 14: Comparison of vehicle motion: (a) without feedback controller, (b) with weak feedback controller, (c) and adequate feedback controller.  $K_p^*$  is 45.2 for this vehicle.  $\tau$  in the controller was 0.1 [s].

## 5 OTHER STUDIES WITH “UOT ELECTRIC MARCH II”

We have studied several motion control issues around EV. Experimental evaluation with “UOT Electric March II” will clarify their validity. Some of these topics are shortly introduced here.

### 5.1 ROAD CONDITION ESTIMATION [2]

The road surface condition is quite useful information for the motion controller. This information will enhance the performance of ABS or TCS. DYC can avoid unintended excessive torque, and can keep the control torque below the notified road surface limit. Therefore, the road condition estimation is intensively studied for conventional vehicles [9]. The accurate value of wheel input torque will contribute a great deal to the practical and precise estimation. It is available with EV or electric motor, but not so easy with ICV or combustion engine. We have proposed an advanced road condition estimator for EV, which estimates the  $\mu_{\text{peak}}$  value during adhesive driving [2]. Basically it was confirmed with experiments, however, further studies should be carried out.

### 5.2 HYBRID ABS [6]

Generally speaking, HEV has only a small motor for torque assist. Thus the regenerative braking must cooperate with a hydraulic braking system (Fig. 15). This cooperation is designed only for energy efficiency, not for wheel skid prevention. We have proposed “Hybrid ABS (H-ABS)”, which is the cooperative ABS with electric and hydraulic torque. The point is that, HEV’s motor has relatively small but rapid torque output, and hydraulic braking system has large but slow torque generation.

Currently, two approaches are discussed. First approach is the “plug-in H-ABS”. Motor controller is just added to the normal hydraulic ABS, without changing the original ABS controller (Fig. 16). Generally, the ABS controller is an on-off type controller. The plug-in feedback controller prevents the rapid change of wheel velocity with feedback, accordingly compensates the high frequency dynamics of original ABS.

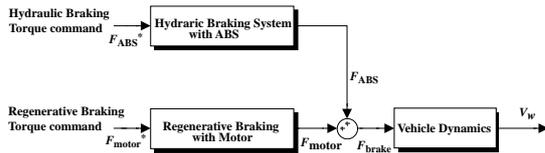


Figure 15: Conventional Regenerative Braking. ABS actuator is only hydraulic one.

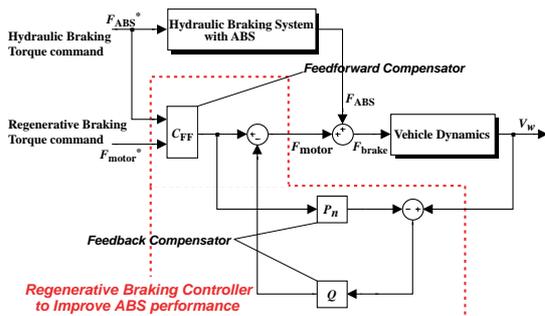


Figure 16: “H-ABS”, cooperative ABS with both electric and hydraulic torque.

The applied feedback controller in Fig. 16 is very similar to the one in section 3. This controller prevents the sudden change of wheel inertia or wheel velocity, thus the wheel velocity oscillation can be suppressed. Simulation results (Fig 17) show this effect typically. Accordingly, the braking distance can be shortened. However, this is just the simple simulation results and further experimental studies should be carried out.

This “plug-in” type’s advantages are, (a) easy to apply and (b) only concerning with wheel velocity, and not using chassis velocity for feedback signals. Another approach is, of course, to design both regenerative and hydraulic braking controller. Controller design with frequency-division seems to be effective with our basic simulations. Experimental study of this method is also planned with “UOT Electric March-II”.

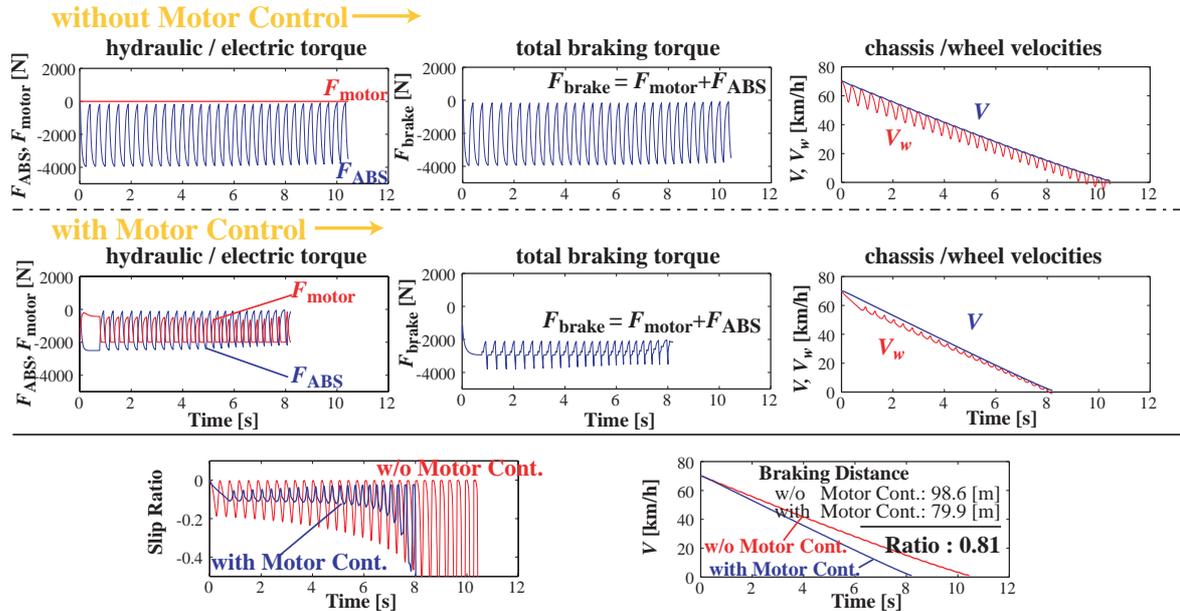


Figure 17: Effect of plug-in H-ABS. Upper row shows the data of simulated conventional ABS. Simple on-off ABS logic causes oscillation. Applied controller with electric motor can suppress this oscillation with compensating the high frequency dynamics (middle row). Consequently, slip ratio oscillation is relatively small and braking distance is shortened (lower row) with proposed methods.

## 6 CONCLUSION

In this paper, the novel experimental EV “UOT Electric March II” is introduced. This 4 wheel motored EV is expected to play an important roll in the motion control studies. The individual research topics, which will be demonstrated with this EV, are also mentioned. Please refer each paper listed below, since the details of these topics are omitted here. In addition, farther information of our EV is available at: [www.hori.t.u-tokyo.ac.jp/997/sakai](http://www.hori.t.u-tokyo.ac.jp/997/sakai).

Again the point is the electric motor’s advantage: quick and accurate torque generation and distributed torques. Currently main concerning around EV is energy efficiency. In the near future, control issue will be another major topics. We will continue our effort toward that day.

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