ECO- and Human-friendly Motion Control for Support of Secure Life

Yoichi Hori, Sehoon Oh, Takeshi Fujii, Dejun Yin, Kiyotaka Kawashima, Takehiro Imura, Kengo Yoshida, Valerio Salvucci, Masamitsu Satake, Kunio Kobayashi, Taichi Ishihara, Hiroyuki Okabe

Department of Electrical Engineering, Faculty of Engineering,
University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 153-8505 113-8656

hori@iis.u-tokyo.ac.jp

***Abstract*— In this paper, Eco-friendly electric vehicle and human-friendly assist device are suggested to support secure life. At first, contactless power supply is studied to make electric vehicle more eco-friendly and electric double layer capacitor, so called supercapacitor is adopted to store the energy for vehicle. In addition to the eco-friendliness, to make human life secure, we develop slip prevention control, smooth torque assist on gearshift, rolling stability control based on electronic stability program and active safety steering for electric vehicle. As human-friendly motion control applications, impact force control is proposed to make electric doors in trains safe, and a new robot configuration based on human muscle system is developed.**

***Index Terms*— electric vehicle, contactless power transfer, magnetic coupling, supercapacitor, motor assisted automatic transmission system, transmissible torque estimation, torque reduction characteristic, rolling stability control, active safety steering, impact force control, bi-articular muscle, impedance matching ellipsoid**

I. Introduction

Advanced motion control can contribute to human society by making devices more eco-friendly and human-friendly. Electric Vehicle (EV) has been highlighted recently due to its eco-friendliness and many researches on EV have been done in various ways. For greater popularization of EVs, the energy storage device and its supply are critical problems. We have developed EV driven only by ñElectric Double Layer Capacitors (EDLCs)ò, which have various advantages compare with batteries. In this paper, we propose vehicle control using this capacitor vehicle. Contactless power transfer is also suggested as a novel power supply system to the EDLC.

Human-friendly motion control is another key word to establish secure life. As society has more elderly people and decreasing birth rate, we need assistance from electrically driven devices. Human-friendly motion control will be able to control these devices in a safe way based on advanced motion control.

This paper is organized as follows; In Section II, novel topics on EV control including contactless power transfer and supercapacitor are proposed. In Section III, human-friendly motion control applications for electric door and a robot are suggested.

II. Electric Vehicle's Advantages and Application for Vehicle Motion Control

Electric vehicle can realize high performance motion control utilizing advantages of electric motors which internal combustion engines do not have. EV has the following four remarkable advantages [1]:

-Motor torque response is 10-100 times faster than that of internal combustion engine's one. This enables to realize high performance adhesion control, skid prevention and slip control.

-Motor torque can be measured easily by observing motor current. This property can be used for road condition estimation.

-Since an electric motor is compact and inexpensive, it can be equipped for each wheel. This feature realizes three-dimensional high performance vehicle motion control.

-There is no difference between acceleration and deceleration control. This actuator advantage enables high performance braking control.

To accomplish secure life in the future, we develop some new motion control of EVs making use of these advantages efficiently.

A. Contactless Power Transfer using Magnetic Coupling of Resonance with Robust to Air Gap and Position Variations for EV

EV cannot cover a long distance driving like gasoline or diesel vehicles. Therefore, we have to develop new techniques to charge EVs quickly, several times a day. Contactless power transfer is best solution to this problem (Fig. 1). Technology of contactless power transfer is mainly classified three. Electromagnetic induction, microwave power transmission and electromagnetic resonant coupling. In electromagnetic induction, air gap is short and position variations are poor [1]. In microwave power transmission, air gap is very long but efficiency is very low [2][4]. On the other hand, in electromagnetic resonant coupling, air gap is long and it has potential for redundancy of position variations [5][6]. In this paper, redundancy to air gap and position variations is discussed (Fig. 2).

From Fig. 3, it is observed that when air gap changes resonant frequencies and efficiency also changes. However, efficiency is constant until resonant frequencies become one. Efficiency with position variations is shown in Fig. 4. With some gaps and over 150mm position variation, there is high efficiency. 150mm is the same in length of a half of antenna diameter. Fig. 5 shows efficiency with position variations not only in x-direction but also in z-direction by electromagnetic field analysis. And these results indicate that this antenna and this type of contactless power transfer is more redundancy for air gap and position variations.

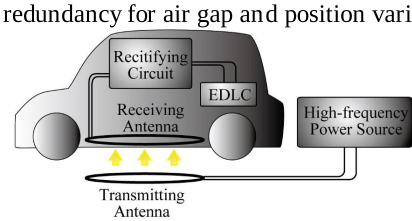


Fig. 1 Whole system of contactless power supply

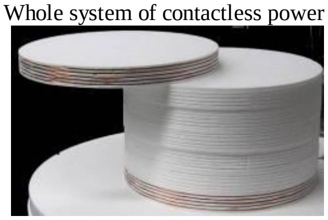


Fig. 2 Transmitting of antenna and Receiving antenna with position variations

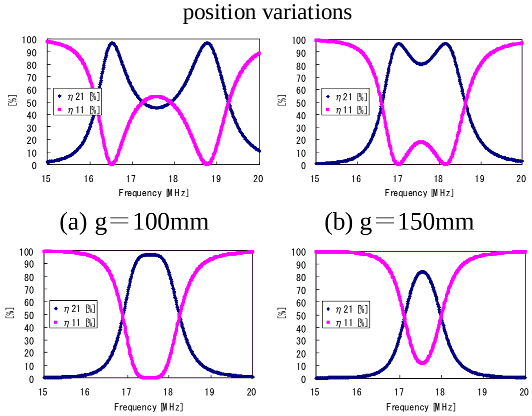


Fig. 3 Efficiency with air gaps
(r＝150mm, n＝5, p＝5mm)

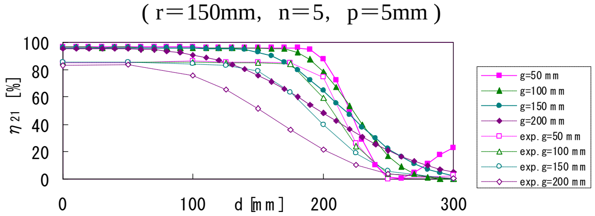


Fig. 4 Efficiency with position variations

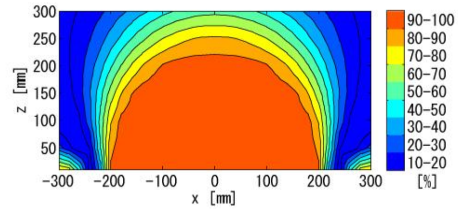


Fig. 5 Map of efficiency with position variations

B. Motor-Assisted AMT System driven by Supercapacitors and Disturbance Observer-based Controller

Motor-assisted AMT control systems are highly efficient transmission systems. The concept of these systems is shown in Fig. 6. In these systems, a motor generates driving torque only when the neutral gear or clutch is pressed while shifting.

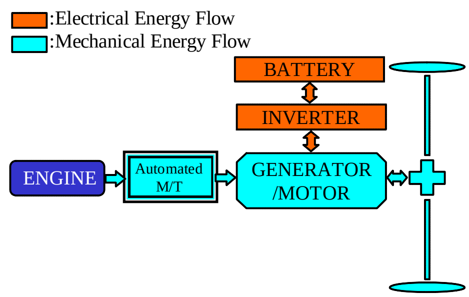


Fig. 6. The concept of Motor-Assisted AMT

In these systems, the required torque should be very large and generated quickly, but it need not to be applied for a long time. Therefore, EDLCs are suitable energy storage devices for producing large power instantly in these systems.

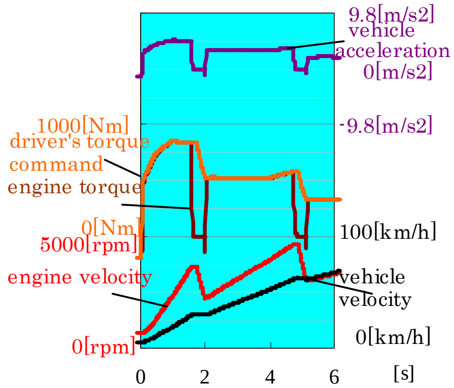
To accomplish both torque requests and to operate this system smoothly, we propose a torque control method applied with disturbance observer-based controller. By using this proposed method, we can get following three advantages;

(i) To control total driving torque to accelerate smoothly,
(ii) To improve the response of driving torque,
(iii)To control electric motor torque according to the status of capacitors.

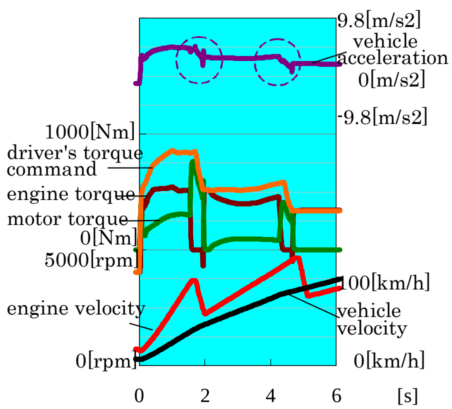
Fig. 7 shows a simulation result. From Fig. 7(b), it is observed that by motor-assisted AMT control, the vehicle acceleration does not decrease with decreasing engine velocity; while shift change. This result shows that smooth gearshift operations can be realized with the proposed control.

C. Anti-Slip Control based on Maximum Transmissible Torque Estimation

In the research of traction control, the dynamic longitudinal model of the vehicle can be described as in Fig. 1 and (1)-(3).



a) without motor assist



b) with motor assist

Fig. 7. Simulation result of torque-assisted AMT control.

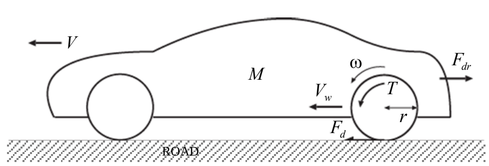


Fig. 8. Dynamic longitudinal model of vehicle.

$$J_w\dot{\omega} = T - rF_d \qquad (1)$$

$$M\dot{V} = F_d - F_{dr} \qquad (2)$$

$$V_w = r\omega \qquad (3)$$

A primary torque controller is designed as in Fig. 9, in which the limiter with a variable saturation value is adjusted to realize the control of torque output according to the dynamic situation. Under normal conditions, the torque reference is expected to pass through the controller without any effect. On the other hand, when on a slippery road, the controller can constrain the torque output to be close to T_{max} which ensures no slip occurs while keeping the system stable.

By contrast to the case without control, Fig. 10 describes the comparison of control performance between the control based on MTTE and that using MFC that has been well researched before. The comparison shows that the proposed method can provide a better performance of slip prevention.

D. Skid Prevention in EVs Based on Torque Reduction Characteristic of Electric Motors

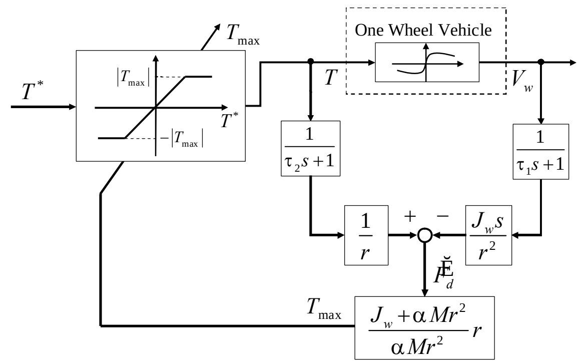


Fig. 9. Primary control system based on MTTE.

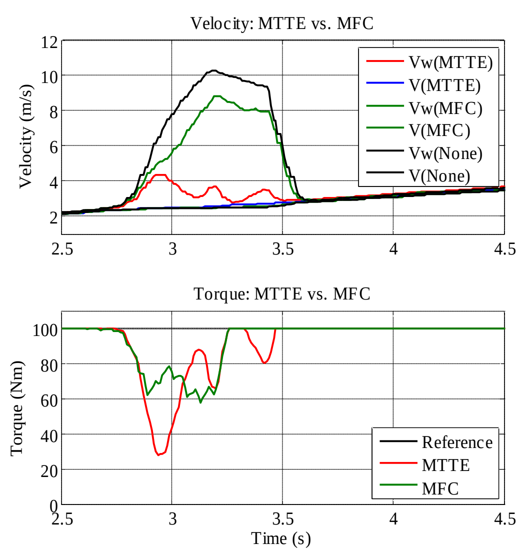


Fig. 10. Comparison of experimental results with two control topology.

In general, the back EMF in a motor decreases the current to drive the motor. However, if the real motor torque is strongly controlled to follow to reference torque (by accelerator pedal), the tire speed will increase drastically when tire slip occurs. In order to maintain the adhesion between the tires and the road surface, it is necessary to decrease the motor torque (current) quickly.

In this study, we modify the current control system. In fact, the current control system is based on a combination of feedforward (FF) control and disturbance observer (DOB), as shown in Fig. 11.

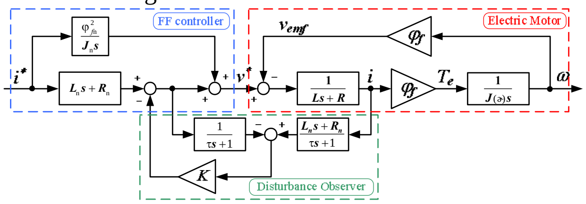


Fig. 11. Block diagram of FF+DOB current control system.

Fig. 12,13 shows the experimental results. The EV used in this study starts with a constant reference current value on a dry asphalt road and enters a wet road at around t=2. Though tire begins to slip when the vehicle enters the wet road, a torque reduction happens and the increase of slipping is suppressed. Additionally, this result shows that the torque reduction characteristics of EVs can be modified by disturbance observer. The effect of skid prevention, or the torque reduction characteristic is improved by setting K small and adjusting τ large.

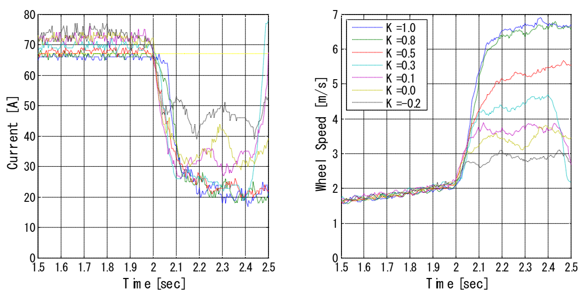


Fig. 12. Experimental results of skid prevention with turning observer gain K of disturbance observer. (τ is constant 0.001.)

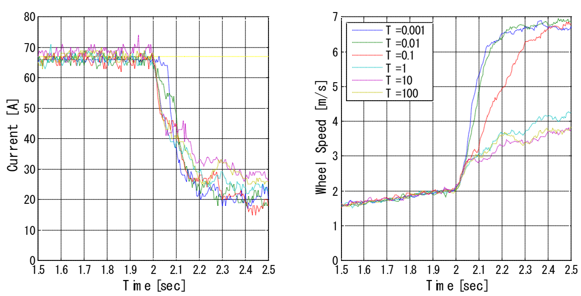


Fig. 13. Experimental results of skid prevention with turning time constant τ of disturbance observer. (K is constant 1.)

E. RSC Based on ESP for In-wheel Motors Electric Vehicle

In this section, a novel rolling stability control (RSC) based on electronic stability program (ESP) for in-wheel motors electric vehicle (EV) is proposed. Fig.14 shows concept of ESP [7] for EV.

ESP consists of two parts; vehicle/road state estimation system (S1) and vehicle dynamics control system (S2). S1 integrates information from sensors (accelerometer, gyro, GPS, suspension stroke, steering angle sensors) and unknown vehicle parameters (mass, body slip angle, roll/pitch angle). Based to the information from S1, S2 controls vehicle dynamics using yawing/rolling stability

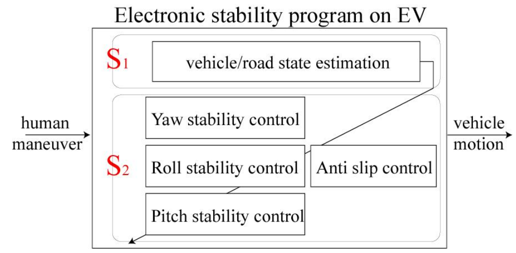


Fig.14 Concept of electronic stability program

control (YSC/RSC), pitching stability control (PSC) and anti-slip control (ASC). According to roll index [8], which is calculated by S1, a proper stability control strategy (YSC, RSC or mixed) is determined. S2 is based on disturbance observer and nominal vehicle state is calculated by computer. If there is error between calculated dynamics and actual ones, it is corrected by differential torque on right and left motors.

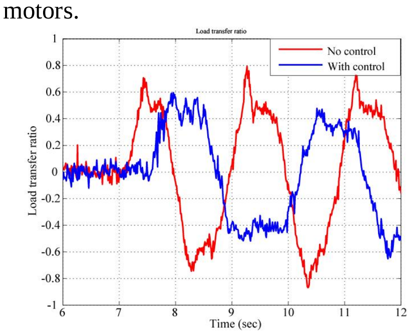


Fig. 15 Experimental result of following capability

Fig. 15 shows experimental result of LTR (Load transfer ratio). LTR is RSC index and if absolute value of LTR is closer to 1, the vehicle has higher possibility of rollover. When the proposed control is activated, peak of LTR is suppressed by differential torque. Even though perfect tracking is impossible due to the torque limitation of in-wheel-motor system and roll dynamics, roll rate by sinusoidal steering input is effectively suppressed.

F. Steering System for Realizing Active Safety

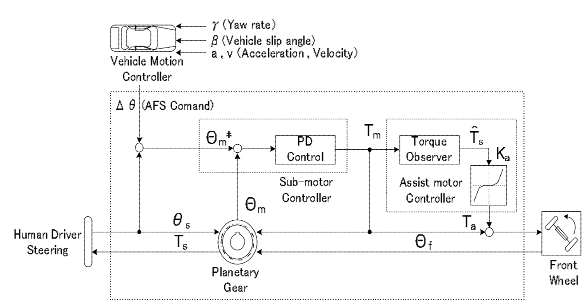


Fig.16. Block diagram of the steering system for AFS

In recent years, the safety technology for a vehicle is required. For example, Active Front Steering (AFS) techniques of stabilizing vehicleόs motion by steering the front wheel automatically according to the state of vehicle are studied but safe operation is very difficult if the problem of the interference between the driver's steering operation and the automatic steering is not solved. We propose the Reactive Torque (RT) control for reducing the interference to the driver by AFS. The block diagram of the steering system proposed is shown in Fig.16.

The system consists of two motors and a planetary gear. The submotor controls the planetary gear so that the front wheel angle follows the AFS command value (PD control). When the interference with the driver is large, especially at start and the end of AFS operation, the submotor generates the reactive torque T_r adapted to the normative model and transmits it to the driver through the steering wheel. The equation of T_r is shown in (4)-(5). The values of K_s and C_s are determined from the load characteristic of the front wheel K_f, C_f and the assistant ratio K_a.

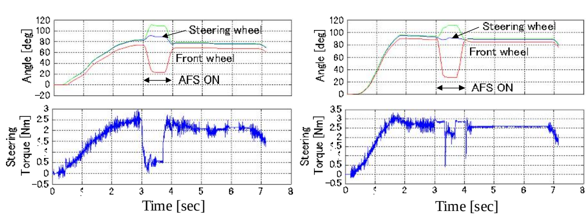
$$T_r = K_s\theta_s + C_s\,\omega_S \tag{4}$$

$$K_s = K_f / (1+K_a),\ C_s = C_f / (1+K_a) \tag{5}$$

The assistant motor usually works as an electric power steering to reduce the steering load of the driver. On the other hand, the system makes the K_a variable and it controls the reactive torque which the driver feels from the road surface so that the driver does not lose steering operation during AFS. The equation of the variable assistant ratio K_a is shown in (6). K_{ao} is a constant value, θ_S is the steering angle, and θ_f is the front wheel angle.

$$K_a = K_{ao}\ (\theta_f / \theta_s) \tag{6}$$

The experimental result of the reactive torque control during AFS operation is shown in Fig.17. AFS was operated 3 to 4 seconds after the experiment started, and the differential angle of the steering angle and the front wheel angle was set to 60 degrees. The system with the control is able to hold driverόs feelings for steering than without the control.



(a). without RT control (b). with RT control

Fig.17. Experimental result of RT Control during AFS operation

III. Application of Human-friendly motion control.

Recently, new electric devices to support human life in direct way start to draw attention. New personal mobility and exoskeletal robots for assistance are the examples. However, there is little discussion on control methodology for these devices.

In this section, we suggest a novel control algorithm and robot configuration on the frame of human-friendly motion control to control such devices in a safe way.

A. Motion Control for Electric Door in Train

Recently, accidents caused by automatic doors have increased. Problems of door systems in the past can be addressed by reflecting the human intervention in the motor control. This can be achieved by sensing whether fingers are caught in the automatic door without force sensors. We research a safer door system using a disturbance observer (DOB) and propose an impact force suppression control of door. Fig. 18 is the proposed control block diagram.

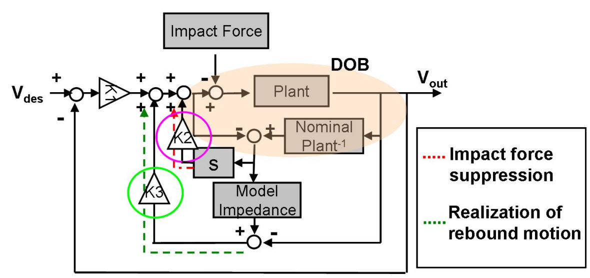


Fig. 18 Control block diagram for impact force suppression

The outer loop is velocity control. Differential force loop can suppress impact force[9]. Model impedance loop can stabilize this control system. Fig. 19 is a simulation result with this control.

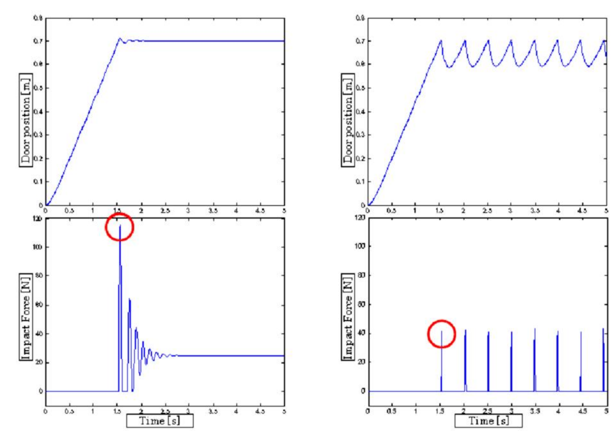


Fig.19 Simulation results of impact force control

Suppression of Impact force can be adjusted with gain K_1 and K_2. And to fix gain K_1 rebounds time can be adjusted. It is confirmed new impact force suppression control of door can suppress impact force.

B. Extended Manipulability Measures for Manipulator based on Bi-articular Muscle Principle

In the past, several manipulability measures have been studied. However they cannot be applied to animal arm and new manipulators based on animal musculoskeletal structure. Animal arm has bi-articular muscle, which works on both two joints simultaneously and has an important role in manipulability and controllability of animal arm. Independence of each joint is lost by existence of this bi-articular muscle, and it is the reason why conventional measures cannot be applied.

This section describes extended manipulability measures and comparison between conventional manipulator (MNP1) and manipulator equipped with bi-articular driving mechanism (MNP2) shown in Fig. 20.

Impedance Matching Ellipsoid (IME) is suggested by Kurazume et al [10]. IME is integrative measures of manipulability. Well-known two measures, Manipulating Force Ellipsoid (MFE) and Dynamic Manipulability Ellipsoid (DME), are typical cases of IME. IME represents transfer characteristic from joint torque to distal force. IME considers acceleration of both manipulator and load. Gravity force and dynamics are also considered.

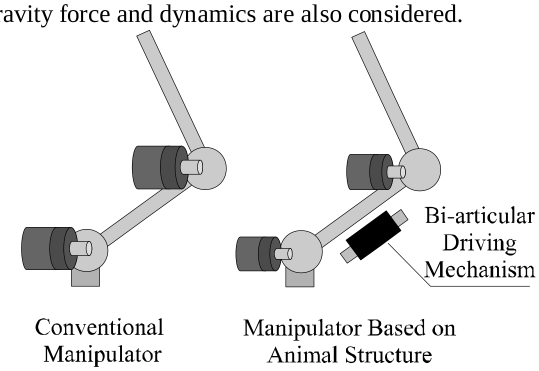


Fig. 20 Conventional manipulator and manipulator based on animal structure

The proposed extended measure is based on IME. Details of derivation are written in our earlier work [11]. Extended measures can represent characteristic of intended manipulator correctly.

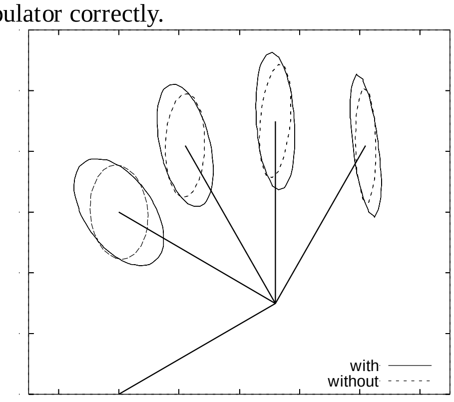


Fig. 21 Each IME is plotted centered end point of respective postures. Dotted line indicates IMEs of MNP1 and solid line indicates IMEs of MNP2. In each posture, angle of joint 1 θ_1 is set to $\pi/6$, and θ_2 changes $\pi/6$, $\pi/3$, $\pi/2$, $2\pi/3$

Variation of IME with several postures is showed in Fig. 21. MNP1 has two actuators in each joint. Maximum output of each actuator is set to 1N. MNP2 has two mono-articular driving actuators and one bi-articular driving actuator. Maximum output of each actuator is set to 2/3N. Especially at flexed posture, characteristic of torque-force transmission is different. To add bi-articular driving mechanism, both output balance and output amplitude is improved. [11] describes quantitative analysis using feature quantity of ellipsoid.

Proposed extended measures enables to fair comparison and correct analysis of both types of manipulator. It is also possible to be utilized for effective design.

IV. CONCLUSION

Motion control is a necessary technology for quality of life and society. We proposed practical applications of motion control to establish secure human life. Electric vehicle and Human-friendly motion control are key concepts we suggest in this application. The projects proposed in this paper revealed new technologies such as the advanced motion control for EV with novel energy supply and human- friendly devices can assist and improve human life.

REFERENCES

[1] Y. Hori, ñFuture Vehicle driven by Electricity and Control-Research on Four Wheel Motored UOT Electric March IIò, *IEEE Trans. on Industrial Electronics*, vol.51, no.5, pp.954-962, Oct 2004.

[2] Y. Kamiya, T. Nakamura, T. Sato, J. Kusaka, Y. Daisho, S. Takahashi, K. Narusawa, ñDevelopment and performance evaluation of advanced electric micro bus equipped with non-contact inductive rapid-charging systemò, *Proc. of the 23rd international electric vehicle symposium (EVS), Electric/ hybrid-electric session*, pp. 1- 14. Dec 2007.

[3] W.C. Brown, ñStatus of the Microwave Power Transmission Components for the Solar Power Satelliteò, *IEEE Trans. on Microwave Theory and Techniques*, vol. Mtt-29, no.12, Dec 1981.

[4] N. Shinohara, H. Matsumoto, ñWireless Charging System by Microwave Power Transmission for Electric Motor Vehiclesò, *IEICE Trans. C*, vol.J87-C, no.5, pp.433-443, 2004.

[5] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, M. Soljaļiĺ, ñWireless Power Transfer via Strongly Coupled Magnetic Resonances,ò *Science Express*, vol. 317. no. 5834, pp. 83-86. Jun. 2007.

[6] A. Karalis, J.D. Joannopoulos and M. Soljaļiĺ, ñEfficient wireless non-radiative mid-range energy transfer,ò *Annals of Physics*, vol.323, no.1, pp. 34-48, Jan. 2008.

[7] E. K. Liebemann, ñSafety and Performance Enhancement: The Bosch Electronic Stability Control (ESP)ò, *SAE Technical Paper Series*, 2004-21-0060, Oct. 2004.

[8] K. Yi, et al, ñUnified Chassis Control for Rollover Prevention, Maneuverability and Lateral Stabilityò, *Proc. of AVEC*2008, pp.708-713, Oct. 2008.

[9] E. Lee, J. Park, K.A. Loparo, ñBang-bang impact control using hybrid impedance/time-delay controlò, *IEEE/ASME Transactions on Mechatronics*, vol. 8, no. 2, pp. 272-277, 2003.

[10] R. Kurazume and T. Hasegawa, ñImpedance matching for a serial link manipulatorò, *Proc. of the 2004 IEEE International Conference on Robotics & Automation,* pp. 4802-4808, May. 2004

[11] K. Yoshida, N. Hata, S. Oh and Y. Hori, ñEvaluation of Robot Arm Equipped with Bi-articular Muscles by Extended Manipulability Measures'ò, *Proc. of the 2008 Japan Industry Applications Society Conference*, 2008