**JPE 6-3-9**

# Position Control of Magnetic Levitation Transfer System by Pitch Angle

Ming-Zhao Liu*, Teruo Tsuji†* and Tsuyoshi Hanamoto*

†*Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology

## Abstract

Magnetic levitation transfer systems are useful for transfer tools in clean rooms and positioning control systems with high precision because of frictionless characteristics. In this paper, the new method is proposed which is a sensorless position. At first, the magnetic levitation is performed by state feedback control with a disturbance observer for each of six axes of the movement of a levitated vehicle. The position of the vehicle is then estimated as the disturbance term of a disturbance observer for a pitch angle which is one of the control axes for the magnetic levitation. In addition, the positioning force is generated by the pitch angle control which gives a tilt to the levitated vehicle so that it generates the horizontal component of force.

**Keywords:** magnetic levitation transfer system, linear drive without any linear driver, disturbance observer

## 1. Introduction

Magnetic levitation transfer systems are useful for transfer tools in clean rooms and positioning control systems with high precision because of frictionless nature. There are many kinds of applications of magnetic levitation system reported in [1] and its references. Especifically, in [1], some kinds of magnetic levitation transfer systems are also introduced, such as 5 axes model or 3 axes model or 2 axes model. However, linear motors are used for the transfer and also a position sensor is used.

In this paper, an idea of generating the positioning force and a new position control method without position sensor are proposed. That is, the magnetic levitation is performed by state feedback control with a disturbance observer for each of five axes of the movement of a levitated vehicle. The position is then computed by the balance of the moment about the pitching direction. The positioning force is generated by the pitch angle control which gives a tilt to the levitated vehicle so that it generates the horizontal component of force. Experimental results show that the position can be computed without a position sensor and the positioning control is achieved by the pitch angle control.

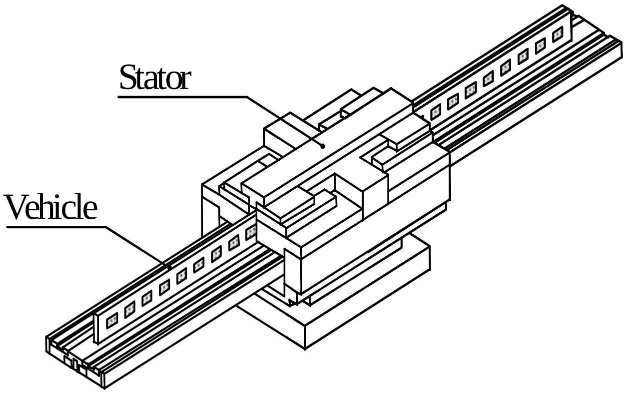

Fig. 1 Overview of the magnetic levitation system

---

Manuscript received August 4, 2005; revised June. 16, 2006

†Corresponding Author: teruo_tsuji@ybb.ne.jp
Tel: +81-92-531-1198, Fax:+81-92-531-0283, Kyushu Inst.
*Life Science and Systems Engineering, Kyushu Institute of Technology

## 2. Magnetic levitation system

In the magnetic levitation transfer system in Fig.1 levitation control and guidance control are performed separately.

In the levitation control, there are four electromagnets in each of upper side and lower side and in the guidance control, there are two electromagnets in each of right hand side and left hand side, as shown in Fig.2. In addition, for the levitation control, the vertical axis, the pitching axis and the rolling axis are assumed for the control axes. For the guidance control, the horizontal axis and the yawing axis are assumed, so the magnetic levitation transfer system is composed by five control axes for levitation as shown in Fig.2. There are 4 gap sensors in the upper side near the electromagnets and 2 gap sensors in the right hand side also near the electromagnets. Thus the 6 gaps between the vehicle and electromagnets are measured by the gap sensors. The outputs of the gap sensors are converted into a digital signal by A/D converters.

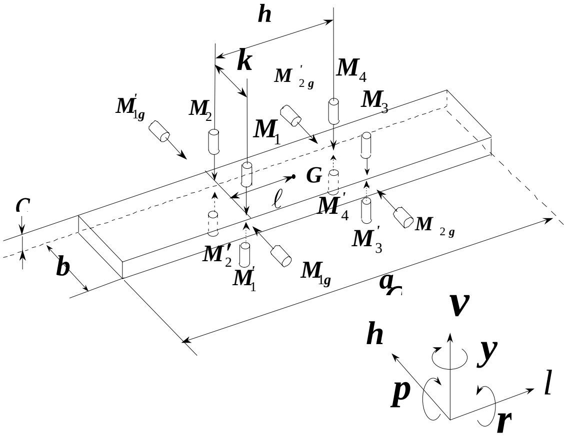

Fig. 2 Allocation of levitating and guiding magnets

## 3. Control Model

Consider the magnetic levitation system shown in Fig.1 and Fig.2, in which an electromagnet exerts attractive force to levitate the vehicle. The system dynamics can be described in the following equations. For levitation control.

$$m\ddot{x}_v = f_1 + f_2 + f_3 + f_4 - mg \tag{1}$$

$$I_r\ddot{x}_r = \frac{k}{2}(f_1 + f_2) - \frac{k}{2}(f_2 + f_4) \tag{2}$$

$$I_p\ddot{x}_p = l(f_1 + f_2) - (h - l)(f_3 + f_4) \tag{3}$$

For guidance control,

$$m\ddot{x}_h = f_{1g} + f_{2g} \tag{4}$$

$$I_i\ddot{x}_i = \ell f_{1g} + (h - \ell) f_{2g} \tag{5}$$

For position control,

$$m\ddot{x}_l = f_\ell \tag{6}$$

where $m$ is the mass of the levitation vehicle, $I_i, (i = r, p, y)$ are the moment of inertias of the role, pitch and yaw direction; $g$ is the gravity acceleration; $x_v$ is a vertical position of the centre of the gravity of the vehicle, $x_r$ is a rolling angle, $x_p$ is a pitching angle, $f_1, f_2, f_3, f_4$ are the attractive force from upper and lower magnets; $x_h, x_y$ are the horizontal position for the guide and the yawing angle, $f_{1g}, f_{2g}$ are the attractive forces for guidance control by $M_{g1}$, $M'_{g1}$ and $M_{g2}$, $M'_{g2}$ respectively. $h, k$ are the distances between the magnets as shown in Fig.2. $l$ is the distance from the midpoint of $M_1$ and $M_2$ to the center of the gravity of the vehicle. That is, $x_l$ is equal to $l$. $f_l$ is the linear driving force of the vehicle which is produced by $f_1, f_2, f_3, f_4$ in the transfer control, as shown in the next section.

## 4. Controller Design

### 4.1 Disturbance observer

From (1)-(6), the following discrete systems are obtained.

$$y(j) = Cx_i(j) \tag{7}$$

$$x_i(j+1) = \Phi x_i(j) + GU_i(j) \tag{8}$$

where

$$C = [1 \quad 0],\ \Phi = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix},\ G = \begin{bmatrix} \frac{1}{2}\Delta t \\ 1 \end{bmatrix}$$

$$i = v, r, p, h, y, l$$

and $\Delta t$ is the sampling time, $j$ is the frequency of the sampling time. For the control inputs

$$U_v = \frac{1}{m}\left(f_1 + f_2 + f_3 + f_4 - mg\right) \tag{9}$$

$$U_r = \frac{k}{2I_r}\left[\left(f_1 + f_3\right) - \left(f_2 + f_4\right)\right] \tag{10}$$

$$U_p = \frac{1}{I_p}\left[l\left(f_1 + f_2\right) - \left(h - l\right)\left(f_3 + f_4\right)\right] \tag{11}$$

$$U_h = \frac{1}{m}\left(f_{1g} + f_{2g}\right) \tag{12}$$

$$U_y = \frac{1}{I_y}\left[lf_{1g} - \left(h - l\right)f_{2g}\right] \tag{13}$$

$$U_l = \frac{f_l}{m} \tag{14}$$

Since some disturbances are expected such as the change of the mass, the moments of inertia and the modeling error, the disturbance observer is designed. The third component of each state vector, denoted by $x_{i3}$ is designed as the disturbance estimation term to compensate the disturbances mentioned above, thus the disturbance observer is given as follow

$$\hat{x}_i(j+1) = W\hat{x}_i(j) + AU_i(j) + L_i\left(x_{i1}(j) - \hat{x}_{i1}(j)\right) \tag{15}$$

where $i = v, r, p, h, y, l$

$$W = \begin{bmatrix} 1 & \Delta t & \frac{1}{2}\Delta t^2 \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix}, A = \begin{bmatrix} \frac{1}{2}\Delta t^2 \\ 1 \\ 0 \end{bmatrix}, L_i = \begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix}$$

$L_i$ , $i = v, r, p, h, y, l$ are observer gains which is given by the pole allocation method. Thus, a state feedback controller is given by

$$U_i(j) = -S_i\hat{x}_i(j) \tag{16}$$

where

$$S_i = \left[s_{i1} \quad s_{i2} \quad 1\right], \qquad i = v, r, p, h, y, l$$

As shown above and as one of the proposals of the paper, this controller with the disturbance observer enables the magnetic levitation even for arbitrary position of the vehicle without the position sensor. Moreover, the position of the vehicle can be also estimated by the disturbance term of the observer of the pitch direction. For reference, the state feedback controller for each axis is given also by the pole allocation method.

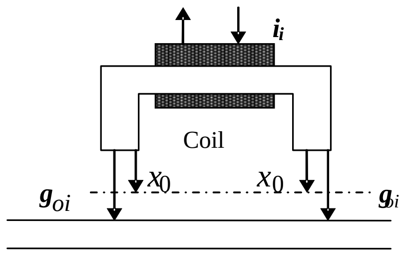

Fig.3 Typical model of the electromagnet

Fig.3 shows a magnet and the movable vehicle, where $x_0$ is the reference position of levitation and $g_{oi}$ is the gap length between the magnet and the movable vehicle. Magnetic permeability of the coils of electromagnets (10,200~15,100) is very big, so the coil current of each electromagnet is

$$i_k = g_{oi}\sqrt{\frac{f_k}{k_g}}, \quad k = 1,2,3,4,1g,2g \tag{17}$$

since the attractive force is assumed to be given by the equation

$$f_k = k_g\frac{i_k^2}{g_{oi}^2}, \; k = 1,2,3,4,1g,2g \tag{18}$$

where, $k_g$ is a proportional coefficient. The time constant of the coil current circuit (0.0004[s]) is neglected, and this modeling error would be considered as disturbance.

## 4.2 Sensorless Controller

For the position control system, from Fig.3 the following relation is given

$$m\ddot{x}_l = F\sin x_p \approx Fx_p \tag{19}$$

and since $F = mg$ , thus

$$\ddot{x}_l = gx_p \tag{20}$$

This is also reduced to the discrete time system and $x_p$ is determined also by the state feedback of $x_l$ . For more detail, $x_p^*$ is determined by the estimated $x_l$ and its numerical derivative as a PD controller, and then $x_p$ is realized by (16). In the experiment, the control response of $x_p$ is sufficiently short compared with the control response of the position, so that the delay by the control response of $x_p$ can be neglected.

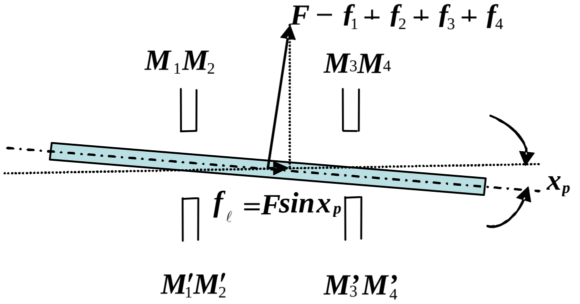

Fig. 4 Principle of position control

For the position sensorless system, $x_l$ can be estimated by (21) which comes from the balance of the moment about the pitching direction as shown below

$$\hat{x}_l(j) = \frac{f_3 + f_4 - f_1 - f_2}{f_1 + f_2 + f_3 + f_4} \times h \tag{21}$$

where $h$ is again the distance between $M_1$ and $M_3$ in Fig.2 or Fig.4.

## 5. Experimental results

The experimental system is shown in Fig.5a and 5b. Details of the controller are as follows. The controller mainly consists of a CPU board, two A/D boards, two D/A boards, S/H board, P-I/O board and six boards of power amplifiers which drive the coils of the magnets for levitation and guidance.

a. CPU: IMS T800-G25S TRANSPUTER,
    64 bits floating decimal system Instruction Cycle 12 nsec,
    Program Language C language
b. A/D board: DVME-611B, Totally 32 channels,
    Conversion resolution 12 bits,
    Conversion cycle 250 kHz,
    Conversion range ± 10 V
c. D/A board: DVME-628, Totally 8 channels,
    Conversion cycle 166.6kHz,
    Conversion range ± 10 V
d. S/H boad (Sampling and Hold):
    16 channels, Resolution 16 bits,
    Settling time 6 micro sec, Conversion range ± 10 V
e. P-I/O board (Parallel Input/Output Board):
    48 channels, 16 bits for a channel
f. Power Amplifier board:
    Maximum rating current 5 Amps,
    Instantaneous maximum current 10 Amps

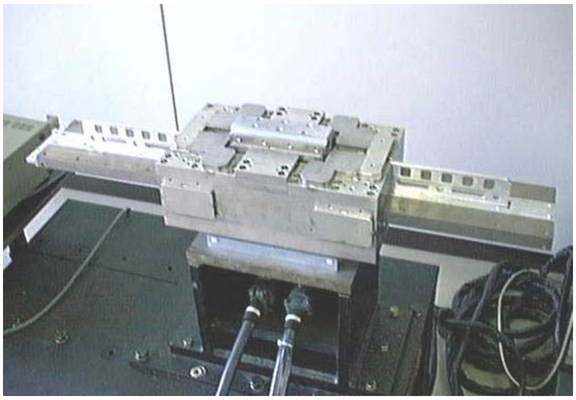

Fig. 5a Photo of Moving vehicle and stator

Fig. 5b Boards and Display of Control system

The mass, size and moments of inertias of the vehicle as follows:
mass $m = 6.7kg$, length $a = 80cm$, width $b = 11cm$, thickness $c = 1.8cm$. The moment of inertia of the role is $I_r = 0.00072\text{Nms}^2$, the moment of inertia of the pitch is

$\boldsymbol{I_p} = 0.3196\text{Nms}^2$ and the moment of inertia of the yaw direction is $\boldsymbol{I}_\text{y} = 0.3265\text{Nms}^2$.

As stated above, the gains of state feedback controller are given by the pole allocation method as follow

$$\begin{aligned} \boldsymbol{S_v} &= [0.94 \quad 0.95 \quad 1] \\ \boldsymbol{S_r} &= [0.75 \quad 0.75 \quad 1] \\ \boldsymbol{S_p} &= [0.91 \quad 0.99 \quad 1] \\ \boldsymbol{S_l} &= [0.9999 \quad 0.9998 \quad 1] \end{aligned}.$$

The observer gains are also given as follow

$$\begin{aligned} \boldsymbol{L_v} &= [0.98 \quad 0.95 \quad 1] \\ \boldsymbol{L_r} &= [0.85 \quad 0.75 \quad 1] \\ \boldsymbol{L_p} &= [0.99 \quad 0.98 \quad 1] \end{aligned}$$

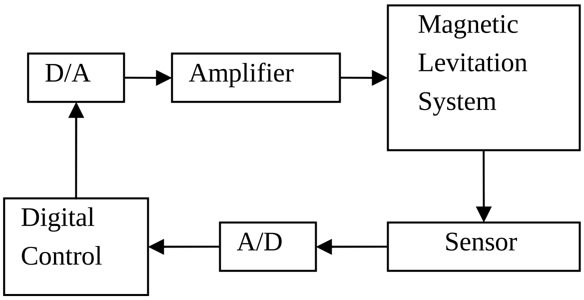

Fig. 6 Control System

Fig.6 shows the flow of the signal between the magnetic levitation system and its controller. The gaps between the vehicle and the electromagnets are measured by the sensors. The outputs are converted into digital signal by A/D converter. So the digital controller computed the force of electromagnets by the digital signal, and the current reference values are computed, then they are converted by the D/A converters, the currents are followed by the amplifiers.

Here, the control purpose is to set the position of the vehicle to the center of the stator. By the application of Section **4**, the pitch angle $\boldsymbol{x_p^*}$ which is the control input for the position $\boldsymbol{x_l}$ is shown in Fig.7. The estimated position $\hat{\boldsymbol{x}}_{\boldsymbol{l}}$ and the measured position by the external laser sensor are shown as Fig.8 and Fig.9. These two responses coincide with each other. This shows that the sensorless position control is possible.

Moreover on the vehicle we put a weight, at the zero position where the vehicle is levitated at standstill. The center of gravity is moved by putting a weight on the vehicle. This means that the target position is moved. As a result, the control action is performed and the vehicle is moved to the target position. Fig.10 shows the response of the reference of the pitch angle $\boldsymbol{x_p^*}$ as control input and Fig.11 shows the estimated position $\hat{\boldsymbol{x}}_{\boldsymbol{l}}$. Fig.12 shows the measured position of the vehicle from the initial position. In the other words, this shows that the distance of movement of the center of gravity is about 1.2 cm.

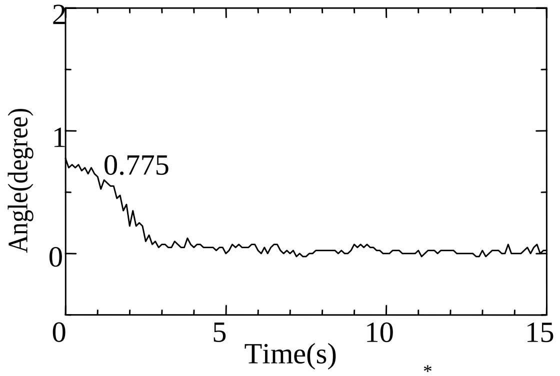

Fig. 7 The control target $\boldsymbol{x_p^*}$

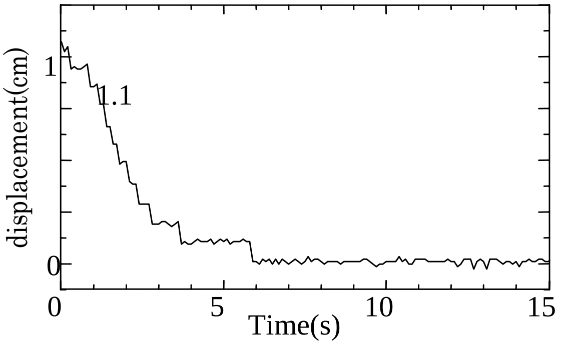

Fig. 8 Response of estimated position $\hat{\boldsymbol{x}}_{\boldsymbol{l}}$

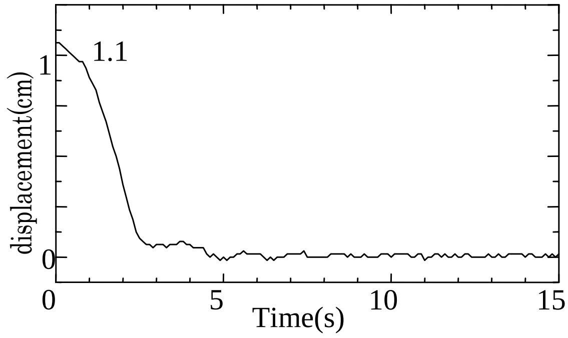

Fig. 9 Measured response of $\boldsymbol{x_l}$

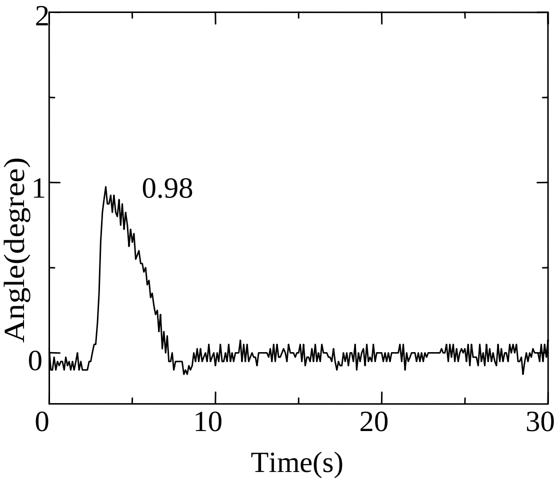

Fig. 10 Response of the control reference $x_p^*$

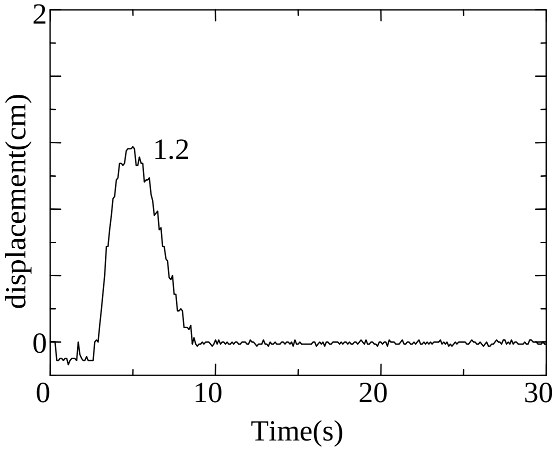

Fig. 11 Response of $\hat{x}_\ell$

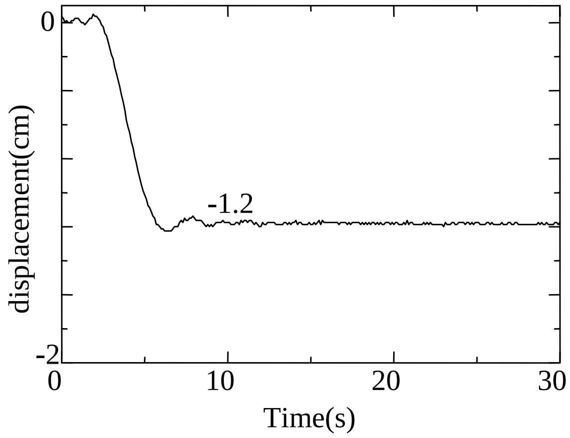

Fig. 12 Measured response by the external position sensor

## 6. Conclusions and Discussions

In the paper the disturbance observer is used in the magnetic levitation control system. A new idea of the sensorless position control method is proposed which completes the positioning control by the pitch angle without any linear driver. By the experimental results, the magnetic levitation by the disturbance observer and the position control by the pitch angle are confirmed to be possible. That is, generally, the system which includes a magnetic system is highly nonlinear and this means the linear model contains a considerable modeling error. In addition, a change in mass or the movement of the vehicle position is also a modeling error. Our experimental results show that the disturbance observer is proved not only to compensate the modeling error for magnetic levitation but also to tell the position of the levitated vehicle without a position sensor. Also, the pitch angle with the gravity acceleration is proved to be a driving force for the control of the linear motion of the vehicle.

## References

[1] The Magnetic Levitation Technical Committee of The Institute of Electrical Engineer of Japan, "Magnetic Suspension Technology", CORONA PUBLISHING CO., LTD. JAPAN,1993.

[2] R.D. Qi, T. Tsuji, Z.J. Yang, R. Oguro, "H-infinity Control Approach to a Magnetic Levitation System by 4 Points Attraction with Nonlinear Characteristics", Electrical Engineering in Japan, Vol.115, No.4, pp110-122(1995).

**Ming-Zhao Liu** was born in JiLin, China, on October 13, 1977. He received B.S. degrees from Beihua University in 2000 year in JiLin China. In 2003 he received M.S. degree from the master course in the Graduate School of Life Science and Systems Engineering in Kyusyu Institute of Technology in Fukuoka Japan and presently. He is in the doctoral course. His research is a control of magnetic levitation system.

**Teruo Tsuji** was born in Nagasaki, Japan on May 17, 1940. He received the B.S.,M.S., and Dr. Eng. degrees in Electrical Engineering from Kyushu University, Fukuoka, Japan, in 1963, 1965 and 1978 respectively. Since 1968 to 2002 he was with the Department of Electrical Engineering, Kyushu Institute of Technology, and since 2002 he has been with Graduate School of Life Science and Systems Engineering where he is presently a Professor. His research interests include control, identification, and control application to magnetic levitation systems and power electronics systems.

**Tsuyoshi Hanamoto** was born on July 22, 1961. He received B.S and M.S degree in Electrical Engineering from Kyushu Institute of Technology in 1984 and 1986, respectively.. In 1986 he joined Kove works of Kobe Steel, Ltd. In 1990 he was engaged Center for Cooperative Research of Kyushu Institute of Technology. from 1997 to 2000 he was with the Department of Electrical Engineering. Since 2000 he has been with the Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology, where he is presently a Professor. His research interests include motor control and power electronics.