JPE 6-1-5

Speed Sensorless Control of Ultrasonic Motors Using Neural Network

Tomohiro Yoshida*, Tomonobu Senjyu†, Mitsuru Nakamura*, Naomitsu Urasaki*,
Toshihisa Funabashi** and Hideomi Sekine*

†*Dept. of Electrical and Electronics Eng., The University of the Ryukyus, Okinawa, Japan
**Power System Engineering Division, Meidensha Corporation., Japan

ABSTRACT

In this paper, a speed sensorless control for an ultrasonic motor (USM) using a neural network (NN) is presented. In the proposed method, rotor speed is estimated by a three-layer NN which adapts nonlinearities associated with load torque and motor temperature into control. The intrinsic properties of a USM, such as high torque for low speeds, high static torque, compact size, etc., offer great advantages for industrial applications. However, the speed property of a USM has strong nonlinear properties associated with motor temperature and load torque, which make accurate speed control difficult. These properties are considered in designing a control method through the application of mathematical models. In these strategies, a detailed speed model of the USM is required which makes actual applications impractical. In the proposed method, a three-layer NN estimates the speed of the USM from the drive frequency, the root mean square value of input voltage and the surface temperature of the USM, where no mechanical speed sensor is needed. The NN speed based estimator enables inclusion of variations in driving conditions due to input signals of the NN involved during the driving state of the USM. The disuse of sensors offers many advantages on both the cost and maintenance front. Moreover, the model free sensorless control method offers practical controller construction within a small number of parameters. To validate the proposed speed sensorless control method for a USM, experiments have been executed under several conditions.

Keywords: Speed sensorless control, ultrasonic motor, neural network

1. Introduction

The USM is a special type of motor, which is driven by the ultrasonic vibration force of piezoelectric elements. It has excellent performance and many other useful features [1], which are not present in other electromagnetic type motors, e.g., high torque, low speed operation, compact in size, no electromagnetic interferences, high holding torque without supply, high response characteristics, and so on. In actual applications, a USM has been used as actuators of cameras, in medical equipment and in high magnetic field uses. The speed characteristics of a USM have a strong nonlinear property. A number of researchers have studied an analytical model of a USM[2-5], which was proposed to evaluate performance. Therefore, the analytical model has a lot of variable parameters which makes applications of the speed model highly impractical[6-8]. On the other hand, accurate speed control is necessary for applications, and we

---

Manuscript received September 29, 2005; revised Nov. 9, 2005
†Corresponding Author: b985542@tec.u-ryukyu.ac.jp
Tel: +81-98-895-8686, Fax: +81-98-895-8708, Ryukyus Univ.
*Dept. of Electrical and Electronics Eng., Ryukyus Univ.
**Power System Engineering Division, Meidensha Corp.

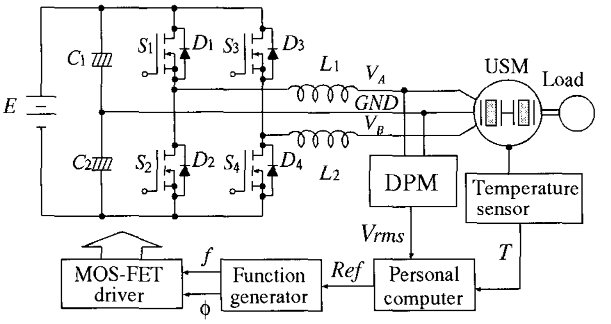


Fig. 1 Drive system for USM

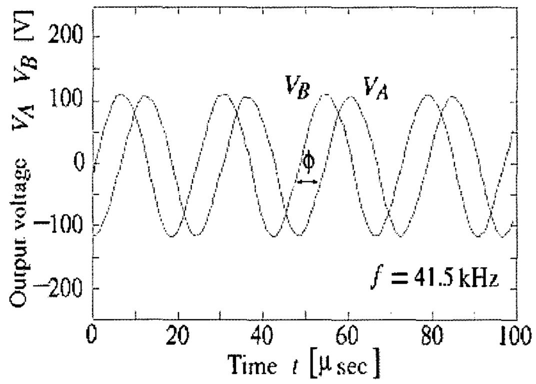


Fig. 2 Output voltages of two-phase inverter

generally require the detailed mathematical model for adapted speed control. To realize high performance and high-precision speed control, accurate speed information is necessary to generate the control input. Generally, the rotor speed is measured by using mechanical sensors such as resolvers or rotary encoders. However, these sensors are usually expensive and bulky, and which increases the cost and size of the drive system [9].

In the proposed method, a three-layer NN is used with off-line training. The drive frequency, the rms of input voltage, and the surface temperature of the USM are used as the input for the NN to estimate the rotor speed. It is well known that the nonlinear identification ability of NNs [10] enable fewer parameters to be used. The validity of the proposed method is confirmed by experimental results.

2. Drive System for USM

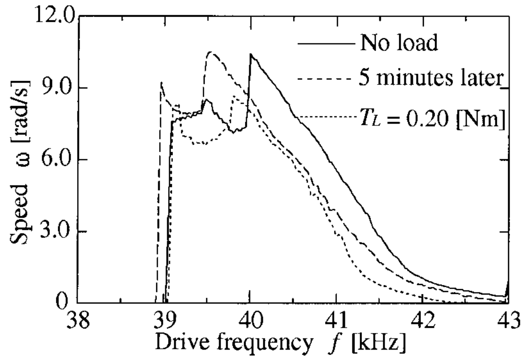
The drive system for the proposed speed control of a USM is shown in Fig. 1 and the design specifications of the experimental USM are given in Table 1. A typical traveling-wave type USM has been applied and consists of a stator and rotor made with an elastic body and piezoelectric elements. The load and rotary encoder are connected with the motor via coupling, the actual motor speed is measured by a 10,000 pulse/revolution rotary encoder to compare the estimated speed with the measured speed. The personal computer implements the controller which calculates the control signal in the proposed method. The control signal is transmitted to the oscillator via a GPIB (General Purpose Interface Bus). Then the inverter generates a two-phase alternating voltage V_A and V_B as shown in Fig. 2. There have been reported many drive systems for USMs based on this two-phase half-bridge inverter[11]. The drive system has three controllable parameters of the two-phase alternating voltage to control the rotor speed, i.e., rms voltage of the sine-wave, drive frequency and phase difference of a two-phase alternating voltage. Advantages of this system include a fast response and a wide controllable range. We applied the drive frequency f to control the rotation speed where the phase difference maintains at $\phi = 90\,\text{deg}$.

Table 1 Motor specifications

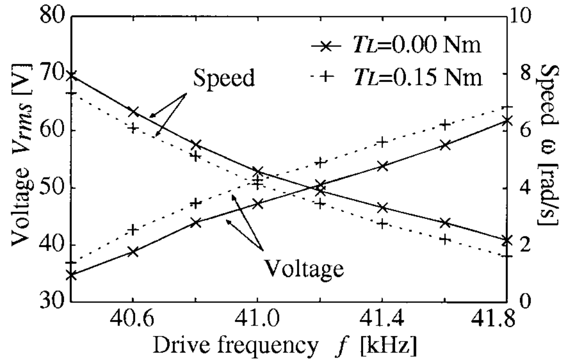
Drive frequency	40 kHz
Drive voltage	100 Vrms
Rated current	53mA/2phase
Rated torque	0.314 Nm
Rated output power	3 W
Rated speed	9.0 rad/s
Mass	0.240 kg

3. Characteristics of USM

The USM has nonlinear speed characteristics as shown in Figs. 3 and 4. Maximum rotational speed is at resonance frequency f_s for the USM. Variations in the surface temperature and motor load torque cause variations in the resonance frequency f_s. As a result, motor speed drops if the motor is driven at a fixed frequency. From Fig. 3(a), it indicates that a motor speed control is necessary and a USM has an unstable control area lower than resonance frequency f_s. We used the

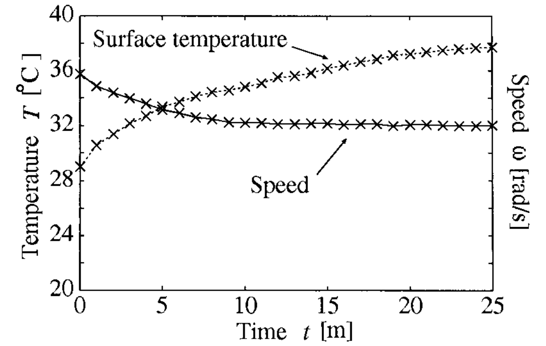


(a) Drive frequency versus rotor speed

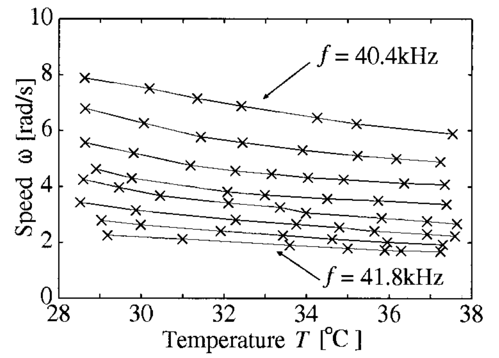


(b) Load torque effect in rotor speed and voltage characteristics

Fig. 3 Torque-speed characteristics



(a) Rotor speed and surface temperature characteristics with time varying



(b) Temperature versus rotor speed for driving frequencies

Fig. 4 Temperature-speed characteristics

control input as a drive frequency, ranging from 40.4kHz to 41.8kHz, because the commanded and actual motor speed needs to be operated with a drive frequency value higher than resonance frequency f_s. Fig. 3(b) shows the characteristics of the input voltage and rotor speed for driving frequency. Using a low drive frequency enables acceleration of the rotor speed. While impedance variations of the USM, related to drive frequency, causes a decreased input voltage. The input voltage V_{rms} increases and rotor speed decreases with applied load torque at the fixed drive frequency. The speed and voltage characteristics are used to estimate rotor speed because the speed variation involved with the applied load torque is reflected by the input voltage V_{rms}.

Fig. 4 shows temperature versus speed characteristics. It shows that surface temperature variation effects rotor speed. Hence, the surface temperature of the USM is used as an input of the speed estimator.

4. Speed Estimation Using NN

Fig. 5 shows a block diagram, which illustrates the speed estimation structure using a NN speed estimator with input voltage V_{rms} [V], drive frequency f [kHz] and surface temperature T [$^\circ$C], as input information. As discussed in the previous section, input voltage V_{rms} represents the effect of load torque and the increase in temperature T effects as the rotor speed drops. In the proposed method, the NN is trained off-line to define the properties of the USM. The off-line training used measured speed characteristics data for each input signal. The estimated rotor speed $\hat{\omega}$ is generated by a trained NN. Then the PI controller calculates the control input according to the speed difference calculated from $\hat{\omega}$ and

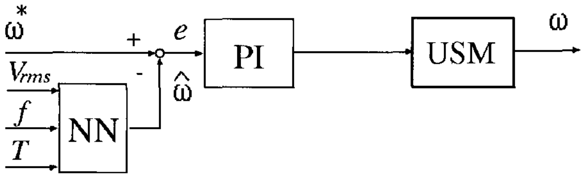


Fig. 5 Block diagram of sensorless speed control using NN

reference rotor speed ω^*. The control input of the PI controller[12] is determined by

$$u_{pi} = k_p e + k_i \int_0^t e dt \tag{1}$$

k_p (=0.5) and k_i (=0.02) are the proportional and integral gains of the PI controller, respectively.

Fig. 6 illustrates the structure of the applied three-layer NN. To make a correct NN output, which follows the supervised signal, the energy function is defined as

$$E = \frac{1}{2}\left(y^* - y_k\right)^2 \tag{2}$$

where y^* is the supervised signal and y_k is the estimated speed of the NN. Table 2 shows the parameters of the applied NN. The experimental system was structured on RTLinux (Real Time Linux), which enables real-time applications. The controller and NN based speed estimator were developed using C language.

5. Experimental Results

The NN off-line training results are shown in Fig. 7. These results show that the proposed method has good speed estimation performance over a wide range and under various drive conditions.

Figs. 8(a) and (b) show the experimental results of speed control by a PI controller using a NN speed estimator under a no load condition. The experimental results demonstrate that the proposed method achieves a good speed control performance when the surface temperature is changed under a no load condition. Figs. 8(c) and (d) show the experimental results under load torque. The experimental results demonstrate that the proposed method achieves a good speed control performance when the surface temperature is changed under load torque $T_L = 0.15$ Nm(50 % of rated torque) In the proposed method, input voltage V_{rms}, drive frequency f, and surface temperature T are used as the inputs of the NN for speed estimation because the speed estimator deals with various drive conditions for applied load torque and variations in temperature. The robustness of the proposed control scheme with temperature variation and load torque is also demonstrated by experimental investigations.

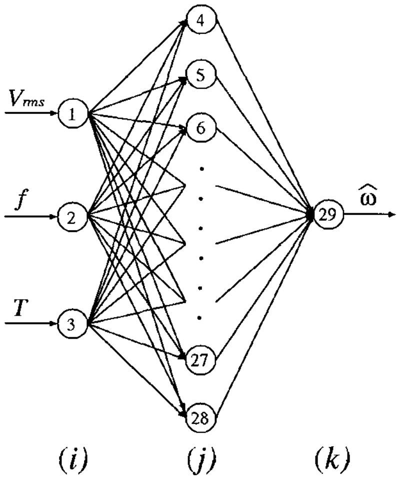


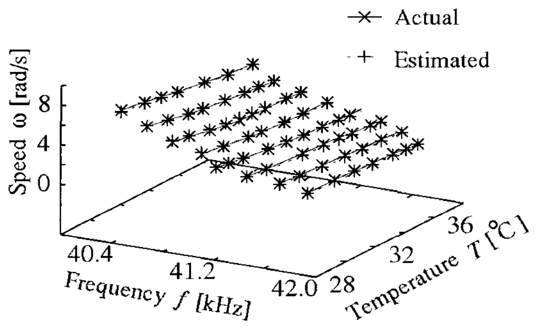
Fig. 6 Structure of NN

Table 2 Parameters of NN

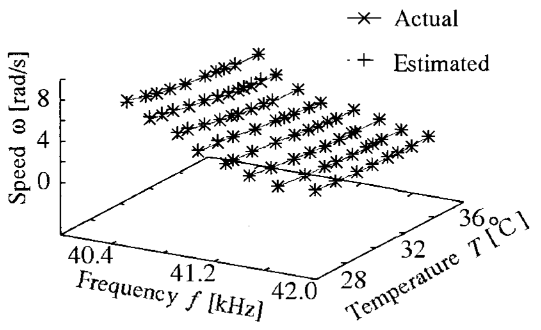
Type	Three-layer NN
Number of layer	$i = 3, j = 25, k = 1$
Learning rate η	0.3
Momentum constant α	0.4
Supervised data	264
Training times	10000
Learning method	back propagation method

6. Conclusions

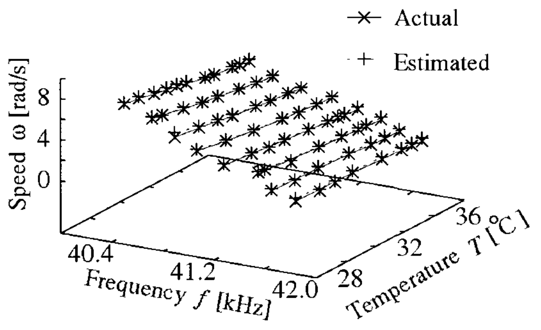
In this paper, a speed sensorless control of a USM which estimates rotor speed using NN, was proposed. In the proposed method, a three-layer NN is used with off-line



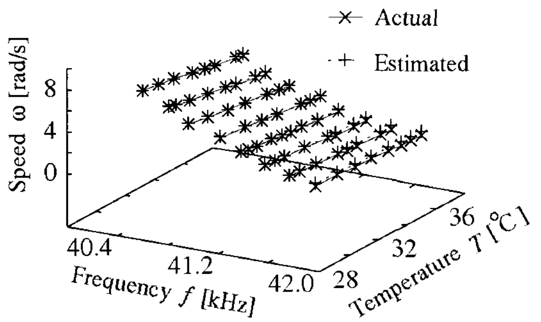
(a) no load



(b) load torque $T_L = 0.05$ Nm

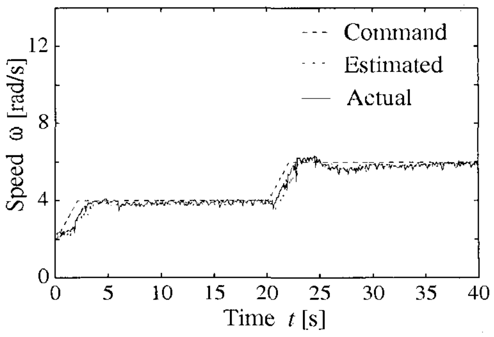


(c) load torque $T_L = 0.10$ Nm

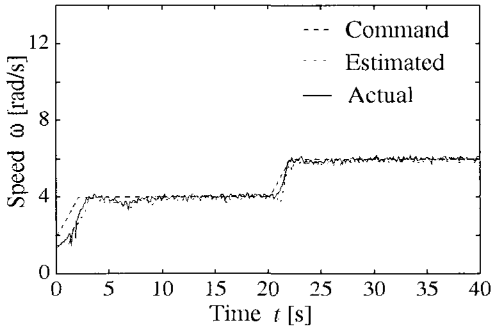


(d) load torque $T_L = 0.15$ Nm

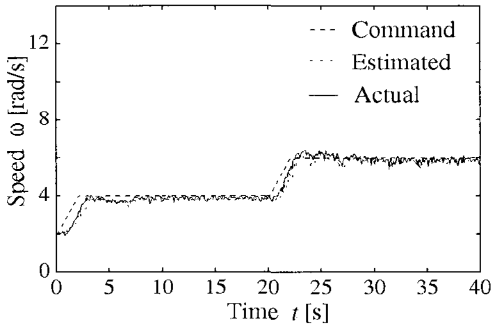
Fig. 7 Results of off-line training



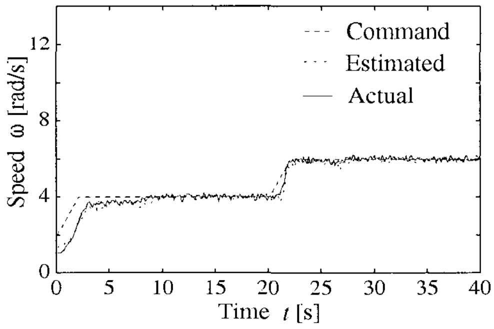
(a) no load, low temperature



(b) no load, high temperature



(c) $T_L = 0.15$ Nm, low temperature



(d) $T_L = 0.15$ Nm, high temperature

Fig. 8 Experimental results of speed control using NN speed estimator training. The drive frequency, input voltage, and surface temperature of the USM are used as input information for the NN speed estimation. This speed estimation structure has robustness for drive condition changes. Also nonlinearities of speed properties are considered. The nonlinear identification ability of the NN has realized enhanced control performance which includes nonlinearities associated with load torque and surface temperatures of USMs. The validity of the proposed method has been demonstrated and confirmed by experimental results.

References

[1] Takashi Kenjyo and Toshio Sashida, "An Introduction of Ultrasonic Motor", Oxford Science Publications, 1993.

[2] E Cerruto, A Consoli, A Raciti, and A Testa, "Modeling of a piezoelectric rotary ultrasonic motor", IEEE Trans. Ultrason., Freq. Contr., Vol. 42, No. 2, pp. 210-224, 1995.

[3] Y. Ming and O. Peiwen, "Performances estimation of a rotary traveling wave ultrasonic motor based on two-dimension analytical model", Ultrasonics 39, pp. 115-120, 2001.

[4] MS Tsai, CH Lee, and SH Hwang, "Dynamic modeling and analysis of a bimodal ultrasonic motor", IEEE Trans. Ultrason., Freq. Contr., Vol. 50, No. 3, pp. 245-256, 2003.

[5] D. Sun, J. Liu and X. Ai, "Modeling and performance evaluation of travelling-wave piezoelectric ultrasonic motors with analytical method", Sens. Actuators A 100, pp. 84-93, 2002.

[6] T. Senjyu, T. Kashiwagi, and K. Uezato, "Position control of ultrasonic motors using MRAC and dead-zone compensation with fuzzy inference", IEEE Trans. Power Electron., Vol. 17, No. 2, pp. 265-272, 2002.

[7] FJ Lin, "Fuzzy adaptive model-following position control for ultrasonic motor", IEEE Trans. Power Electron., Vol. 12, No. 2, pp. 261-268, 1997.

[8] T. Senjyu, S. Yokoda, H. Miyazato, and K. Uezato, "Speed control of ultrasonic motors by adaptive control with a simplified mathematical model", IEE Procces-Electric Power Appl., Vol. 145, No. 3, pp. 180-184, 1998.

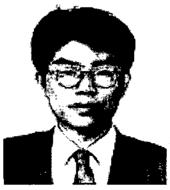
[9] Seong-Hwan Kim, Tae-Sik Park, Ji-Yoon Yoo, and Gwi-Tae Park, "Speed-Sensorless Vector Control of an Induction Motor Using Neural Network Speed Estimation", IEEE Trans. Indust. Electron., Vol. 48, No. 3, pp. 609-614, 2001.

[10] T. Senjyu, H. Miyazato, S. Yokoda and K. Uezato, "Position Control of Ultrasonic Motors Using Neural Network", IEEE International Symposium on Industrial Electron (ISIE'96), pp. 254-259, June 17-20 1996.

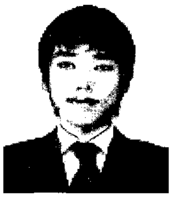
[11] Y. Izuno, T. Izumi, H. Yasutsune, E. Hiraki, and M. Nakao "Speed Tracking Servo Control System Incorporating Traveling-Wave-Type Ultrasonic Motor and Feasible Evaluations", IEEE Trans. Industry Appl. , Vol. 34, o. 1, pp. 126-132, 1998

[12] T. Izumi, H. Yasutsune, Y. Ju Kim, and M. Nakaoka, "New Inverter-Fed Power Ultrasonic Motor for Speed Tracking Servo Application and Its Feasible Evaluations", Proceedings of International Conference on Power Electronics and Drive Systems, Vol. 2, pp. 766-773, 1995.

Tomohiro Yoshida was born in Kagoshima Prefecture, Japan in 1979. He received his B.S. and M.S. degrees in Electrical Engineering from the University of the Ryukyus, Okinawa, Japan, in 2002 and 2004, respectively. In 2004, he joined the Okinawa Electric Power Co., Inc., Okinawa, Japan.



Tomonobu Senjyu was born in Saga Prefecture, Japan, in 1963. He received his B.S. and M.S. degrees in Electrical Engineering from the University of the Ryukyus, Okinawa, Japan, in 1986 and 1988, respectively. He earned his Ph.D. degree in Electrical Engineering from Nagoya University, Nagoya, Japan, in 1994. Since 1988, he has been with Faculty of Engineering, University of the Ryukyus. He is currently a professor in the Department of Electrical and Electronics Engineering. His research interests are in the areas of stability of AC machines, advanced control of electrical machines, and power electronics. Prof. Senjyu is a member of the Institute of Electrical Engineers of Japan.



Mitsuru Nakamura was born in Aichi Prefecture, Japan in 1980. He received his B.S. degree in Electrical Engineering from the University of the Ryukyus, Okinawa, Japan, in 2005. He is currently working toward his M.S. degree in the Department of Electrical and Electronics Engineering, Faculty of Engineering, University of the Ryukyus. His research interests are modeling and control of ultrasonic motors.

Naomitsu Urasaki was born in Okinawa Prefecture, Japan in 1973. He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from the University of the Ryukyus, Okinawa, Japan, in 1996, 1998 and 2004, respectively. Since 1998, he has been with the Faculty of Engineering, University of the Ryukyus. He is currently a Research Associate in the Department of Electrical and Electronics Engineering. His research interests are in the areas of modeling and control of AC motors. Dr. Urasaki is a member of the Institute of Electrical Engineers of Japan.

Toshihisa Funabashi was born in Aichi Prefecture, Japan in 1951. He received his B.S. degree in Electrical Engineering from Nagoya University, Aichi, Japan, in 1975. He received his Ph.D. degree in Electrical Engineering from Doshisha University, Kyoto, Japan, in 2000. In 1975, he joined the Meidensha Corporation, Tokyo, Japan, where he was engaged in research on power system analysis and is a currently senior engineer of the Power System Engineering Division. Dr. Funabashi is a chartered engineer in the U.K. and a member of the IEE and the IEE of Japan.

Hideomi Sekine was born in August 1943. In March 1969, he completed his Masters' degree in Electrical Engineering at Gunma University Graduate School. He became an assistant at the same university in April of the same year. In April 1983, he became an associate professor in the Department of Electric and Electrical Engineering of the Faculty of Engineering of the same University. He has been a professor in the Department of Technology Education of the Faculty of Education, University of the Ryukyus since August of 1996. He obtained a Doctorate degree from Tokyo Institute of Technology, Japan.