https://doi.org/10.20965/jrm.2001.p0074

Paper:

Development of a Robot for Evaluating Tennis Rackets

Junji Furusho*, Masamichi Sakaguchi*, Naoyuki Takesue*, Fuminobu Sato, Takeshi Naruo** and Hiroshi Nagao****

*Dept. of Computer-Controlled Mechanical Systems,
Graduate School of Engineering, Osaka University
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
**Product Development Division, Mizuno Corporation
1-12-35 Nanko Kita, Suminoe-ku, Osaka 559-0034, Japan
[Received Nov. 12, 2000; accepted Dec. 12, 2000]

The development and simulation of robots that have athletic skill close to human beings is very much useful for testing and developing sport goods. This paper discusses the development and simulation of a tennis robot. The developed tennis robot has two joints controlled by a servolike human muscle, and its characteristics are satisfying and similar to a human. The simulation for the whole system including racket, ball and tennis robot is set up. The simulation results agree well with experimental results.

Keywords: Robot, Tennis, Racket, Evaluation, Motor control, Sports engineering

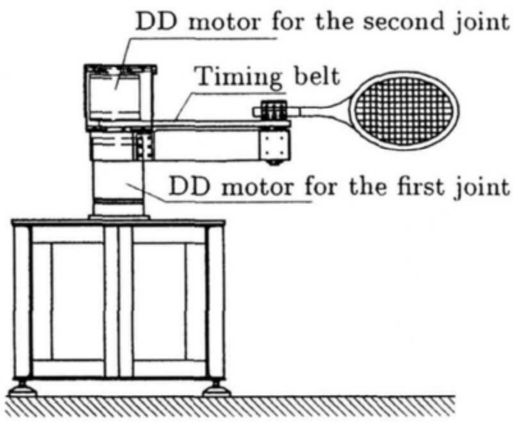


Fig. 1. The tennis robot's appearance.

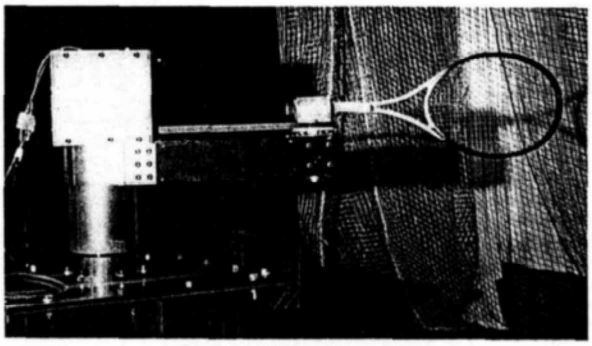


Fig. 2. The tennis robot's photograph

1. Introduction

The development and simulation of a tennis robot is very much useful for testing and developing tennis rackets. As humans hit a ball with a tennis racket, stress and acceleration are generated at the every part of the tennis racket. If a tennis robot can be made which has athletic skill close to a human and is able to reproduce similar states described above, it will become possible to quantitatively appraise tennis rackets grasped by humans. In our study, we aim to develop and simulate such a tennis robot, and make clear human dynamics including muscle characteristics and the mechanism of human motion control.

In this paper, we discuss the structure of the developed tennis robot, and investigate the motion control of the tennis robot in consideration of the mechanism of human motion control. Based on the above, the simulation for the whole system including racket, ball and tennis robot is set up, and the experimental study is made to measure volley characteristics when the racket is grasped differently. It is experimentally confirmed that the developed tennis robot has satisfactory performance in volleying.

2. Tennis Robot Configuration

When humans hit a ball, the motion of the tennis racket is complex which consists of translational motion and rotational motion. In this paper, in order to make the translational and rotational motion of the racket in 2D space possible, the developed robot has two joints as shown in **Fig.1** and **Fig.2**. The main parts of the robot are described below.

Driving System: The first joint is driven by a DD motor (NSK SSB090) directly, and the second joint is actuated by a DD motor (NSK SSB030) through the timing belt. Since these DD motors have little friction and good backward-drivability,[1, 2] the robot system can respond to the instantaneous phenomenon for a ball to col-

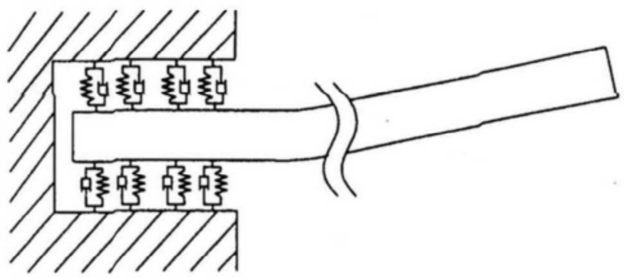


Fig. 3. Model of the grasped part

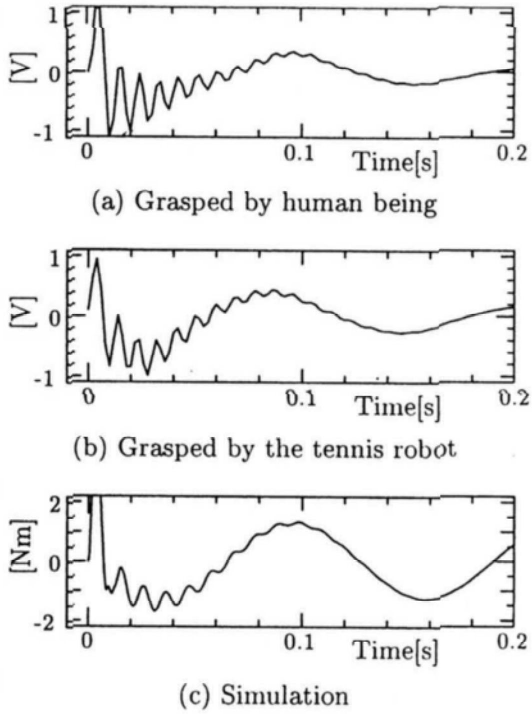


Fig. 4. The strain variations in rackets

lide with a racket.

Arm: The arm of the tennis robot is made of CFRP and aluminum alloy so that the mass of the arm is close to the one of human being.

Grasped part: When the racket is grasped by the tennis robot directly, the obtained characteristics are different from that grasped by human being. By this reason, between the racket and the grasped part, some materials are put to absorb impacts. The materials are selected as viscoelastic materials. Their quality and thickness are chosen so as to be similar to human hand.

3. Viscoelasticity of Grasped Part

In order to select appropriate materials for the grasped part of the tennis robot, we investigate the vibration characteristics and the viscoelasticity of the different kinds of grasped parts.

The vibration characteristics are tested by measuring the strain variations in rackets, when a ball hits the racket grasped by fixed human hand and by the fixed grasped part of tennis robot with viscoelastic materials. In experiments grasped by the tennis robot, we change the material and thickness of the grasped part according to experimental results, and make the vibration characteristics close to that grasped by the human hand. Based on the model shown in **Fig.3**, the simulations are also made corresponding to the above experimental conditions.

A set of results of experiments and simulations is shown in **Fig.4**, where the elastic constant and the viscosity coefficient of the grasped part are 1.2×10^4N/m and 6.0Ns/m in simulation. Through investigating the results of experiments and simulation, we discuss the viscoelasticity of grasped parts, and clarify that the viscoelasticity of grasped parts greatly influences the frequency and damping of the vibration.

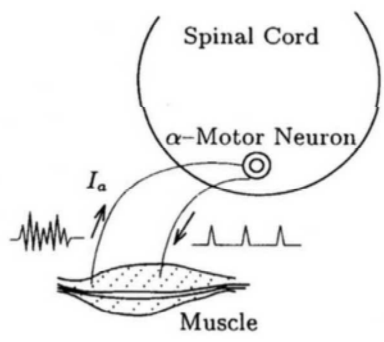


Fig. 5. Simplified control mechanism of muscle

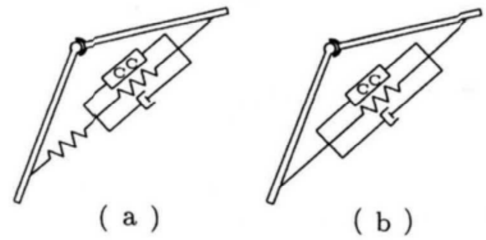


Fig. 6. Muscle model

4. Motion Control

4.1. Motion Control of Human Beings

Considering motion, humans can be replaced by the servo mechanism.[3,4] This is what is called "the thinking method of feedback" in the field of body kinematics and nerve systems.

There is a certain potential difference in the cells of skeletal muscle fibers and nerve fibers. As a muscle is excited, the potential difference varies. The information that the position and rate of the muscle vary with the potential difference can be transmitted by I_a fiber, and the order that the muscle contracts are output by the way of pulse, shown in **Fig.5**. There is a limitation on the output frequency of the pulse; that is to say, the high-frequency

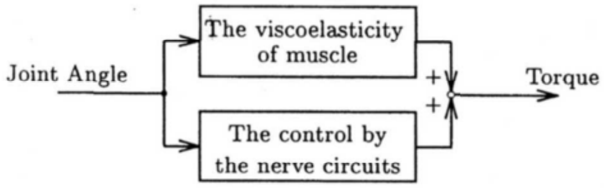


Fig. 7. Control system of skeletal muscle

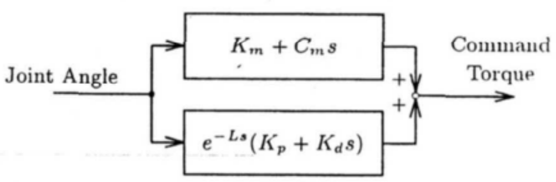


Fig. 8. Control system of tennis robot

variation over the limitation cannot be transmitted.

In addition, the muscle itself has the property of an actuator with viscoelasticity as shown in **Fig.6**, where **Fig.6**(a) is the muscle model in common use, and **Fig.6**(b) is the simple muscle model used in the field of motion physiology.[5] Therefore, skeletal muscle control can be considered as a servo system shown in **Fig.7**.

4.2. Motion Control of Tennis Robot

In order to make the motion control of a tennis robot more similar to that of a human being, based on the mechanism of human motion control described above, the control of the tennis robot is considered as a servo system having feedback control with the information transmission lag in nerve circuits[4] (**Fig.7**). It is shown in **Fig.8**, where K_m is the muscle elastic coefficient, C_m is the muscle viscosity coefficient, L is the time lag representing the information transmission lag in nerve circuits, and K_p, K_d are the feedback coefficients in muscle control system.

5. Simulation

To simulate the whole tennis robot system including the racket, ball and tennis robot, it is necessary to model the whole system. The physical model of the tennis robot is shown in **Fig.9(a)**, and **Fig.9(b)** is the enlarged figure about the racket and the grasped part. In the figure, θ_w is the angle between grasped part and arm, R_w is the distance from the mass center of the grasped part to the rotational center of the wrist, R_E is the distance from the grasping end of racket to the rotational center of the wrist. This section discusses how to build the mathematical model of the whole system and simulate it.

5.1. Assumptions in Modeling

When modeling the whole system, we make the following assumptions:

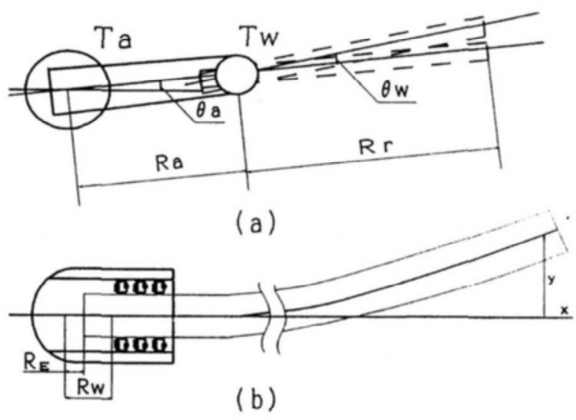


Fig. 9. Model of the tennis robot

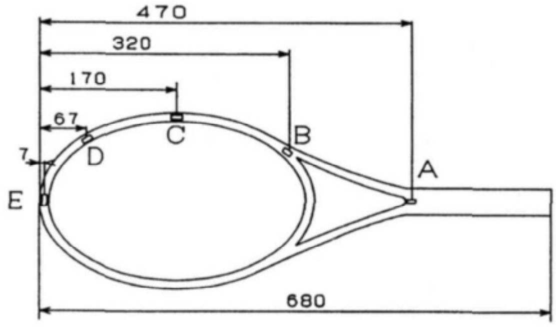


Fig. 10. Position of strain gauges

1. The racket is supposed to a 1D flexible beam, and the racket's deformation is represented by $y(t, x)$. Because the racket's deformation is minute, it can be viewed as linearity.
2. The robot grasped part is shown in the left of the **Fig.9(b)**. It holds a racket through some viscoelastic materials.
3. The ball is regarded as a lumped mass m_B and the force F_B interacting between the ball and the string can be defined by the following formula:

$$F_B = -k_B x_B - c_B \dot{x}_B \quad \dots\dots\dots\dots\dots \quad (1)$$

where x_B stands for relative distance between the ball and the string.

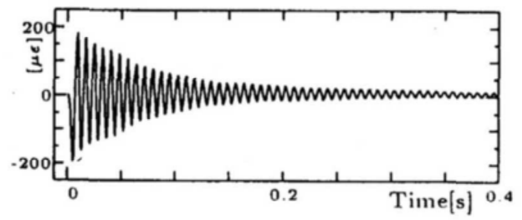
4. The string is regarded as a lumped mass m_G and the force F_G interacting between string and racket can be defined by the following formula.

$$F_G = k_B x_B + c_B x_B - k_G x_G - c_G x_G \quad \dots\dots\dots \quad (2)$$

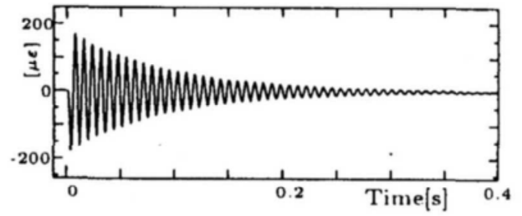
where x_G stands for string's relative deformation to the racket. Actually, in accordance with distribution function $h(x)$, the force F_G acts at the place where the string is stretched.

5.2. Parameter Identification of Racket

In order to identify the parameters of racket, we simu-



(a) Experiment



(b) Simulation

Fig. 11. Strain variations of racket at point B

late the tennis racket.

At first, we make an experiment letting a ball hit the racket hung in the air and measure the strain generated in the several parts of the racket by the strain gauges. The strain gauges are pasted on the A, B, C, D, E positions of the racket, as shown in **Fig.10**.

Next, under the same condition as the experiment, we suppose the racket to a 1D flexible beam and simulate it by means of the RKG numerical integration method. When the simulation results is similar to the experimental results (reference to **Fig.11**), the related parameters used in simulation are as follows:

Ball viscosity coefficient	3.2	[Ns/m]
Ball spring modulus	10147.9	[N/m]
Gut viscosity coefficient	19.0	[Ns/m]
Gut spring modulus	31675.5	[N/m]
Racket viscosity coefficient	5.5×10^{-5}	[Ns/m]

5.3. Dynamic Equations of Motion

The equations of motion of the whole system are given by the following.

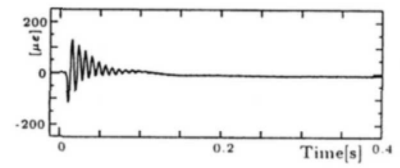
The equation about the rotational motion of the first link arm is

$$(I_a + m_a a^2)\ddot{\theta}_a = T_a - T_w - F_w R_a \quad \ldots\ldots\ldots (3)$$

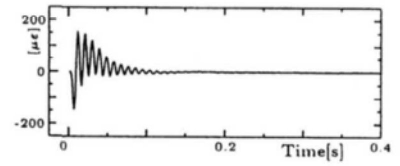
where T_a is the first joint torque, T_w is the second joint torque and F_w is the translational force acting on the grasped part.

The equation about the translational motion of wrist and racket is

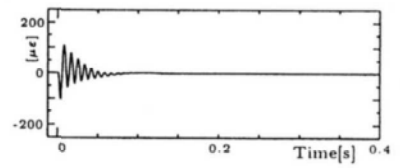
$$m_w(R_a + R_w)\ddot{\theta}_a + m_w R_w \ddot{\theta}_w + \int_0^{R_r} m(x)\{(R_a + R_E + x)\ddot{\theta}_a + (R_E + x)\ddot{\theta}_w + \ddot{y}(t,x)\}dx = F_w - F_G \quad \ldots\ldots (4)$$



(a) Grasped by human being



(b) Grasped by the tennis robot



(c) Simulation

Fig. 12. Strain variations of racket at point B (Volley characteristics)

The equation about the rotational motion of wrist and racket is

$$(I_w + m_w R_w^2)(\ddot{\theta}_a + \ddot{\theta}_w) + \int_0^{R_r} m(x)(R_E + x)\{(R_a + R_E + x)\ddot{\theta}_a + (R_E + x)\ddot{\theta}_w + \ddot{y}(t,x)\}dx = T_w - \int_{R_1}^{R_2} x h(x) F_G dx \quad \ldots\ldots (5)$$

The equation about the racket deformation is

$$\frac{\partial^2}{\partial x^2}\left\{EI(x)\frac{\partial^2 y(t,x)}{\partial x^2} + C_r EI(x)\frac{\partial^2 \dot{y}(t,x)}{\partial x^2}\right\} = -m(x)\left\{(R_a + R_E + x)\ddot{\theta}_a + (R_E + x)\ddot{\theta}_w + \frac{\partial^2 y(t,x)}{\partial t^2}\right\} - \{k(x)y(t,x) + c(x)\dot{y}(t,x)\} - h(x)F_G \quad \ldots\ldots\ldots\ldots (6)$$

where C_r is the damping coefficient of the racket itself, and $k(x)$ and $c(x)$ are the stiffness and the damping coefficients of the grasped part. $k(x)$, $c(x)$ can be expressed by

$$k(x), c(x) = \begin{cases} k_x, c_x & (G_1 \le x \le G_2) \\ & \textit{the grasped section} \\ 0 & (x < G_1, x > G_2) \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$h(x) = \begin{cases} \bar{h}(x) & (R_1 \le x \le R_2) \\ & (\textit{the section where} \\ & \textit{string is stretched}) \\ 0 & (0 < x < R_1, R_2 < x < R_r) \end{cases} \quad \dots \dots \dots (8)$$

which means that $k(x)$, $c(x)$ have certain value k_x, c_x within the section $[G_1, G_2]$.

The boundary condition of the partial differential Eq.(6) is given by

$$\frac{\partial^2 y(t,0)}{\partial x^2} = 0, \frac{\partial^3 y(t,0)}{\partial x^3} = 0$$

$$\frac{\partial^2 y(t,R_r)}{\partial x^2} = 0, \frac{\partial^3 y(t,R_r)}{\partial x^3} = 0 \quad \dots \dots \dots (9)$$

which means that the moment and shearing stress on the both ends of the racket are zero. The equation about the string motion is

$$m_G\{(R_a + R_E + x)\ddot{\theta}_a + (R_E + x)\ddot{\theta}_w + \ddot{y}_{mean} + \ddot{x}_G\} = F_G - F_B \quad \dots \dots \dots (10)$$

where

$$y_{mean} = \frac{1}{R_2 - R_1}\int_{R_1}^{R_2} y(t,x)dx \quad \dots \dots \dots (11)$$

The equation about the ball motion is

$$m_B\{(R_a + R_E + x)\ddot{\theta}_a + (R_E + x)\ddot{\theta}_w + \ddot{y}_{mean} + \ddot{x}_G + \ddot{x}_B\} = F_B \quad \dots \dots \dots (12)$$

Eliminating F_w, F_G, F_B in the above Eqs.(3) to (12), we can obtain the final equations of motion. After identifying the related parameters in the equations, the mathematical model of the whole system is formed.

Using the model described above and the tennis robot's controller given in **Fig.8**, the simulation for the whole system can be carried out.

6. Volley Characteristics

In this section, we discuss the volley characteristics of tennis racket, which is one of the important characteristics to appraise the tennis rackets quantitatively. The volley in this paper means that the ball collides with the tennis racket grasped by human being or tennis robot.

6.1. Racket Grasped by Human Being

As the tennis racket grasped by human being, the volley experiment is done and the volley characteristics are measured. One of the experimental results is shown in **Fig.12(a)**. From the results, we can observe that the strain generated in the racket consists of low-frequency vibration and high-frequency vibration.

6.2. Racket Grasped by Tennis Robot

As the tennis racket grasped by the developed tennis robot, the volley experiment is also done. In this case, the used controller is shown in **Fig.8**. By tuning the parameters in this controller, we can make the measured volley characteristics similar to that grasped by human being, which is shown in **Fig.12(b)**.

6.3. Simulation

Corresponding to the volley experiment, the simulation is carried out using the method described in Section 5. The simulation result of the volley characteristics is shown in **Fig.12(c)**, which is also similar to that grasped by human being.

7. Conclusions

1. A tennis robot was developed which has the impact characteristics close to human being. Its motion control system is a servo system like human muscle.

2. Through investigating the materials put in the grasped part, it is clear that the viscoelasticity of the grasped part has a great influence on the intrinsic vibration. As the appropriate materials are selected for the grasped part, the grasping performance of the tennis robot can be obtained close to a human.

3. As the motion control of the tennis robot is implemented according to the mechanism of human motion control, the volley characteristics of the tennis robot are obtained close to human being.

4. The simulator for the whole system including racket, ball and tennis robot was formed. By comparing the simulation results with experimental results, the related parameters of the tennis robot were identified. The simulation results are satisfying and agreed well with experimental results.

References

1) C.H.An, et al., "Model-Based Control of a Robot Manipulator", The MIT Press, 1988.
2) H.Asada, et al., "Robot Analysis and Control", Wiley-Interscience, 1986.
3) D.A.Winter, "Biomechanics and Motor Control of Human Movement", A Wiley-Interscience Pub., 1990.
4) J.S.Griffith, "Mathematical Neurobiology", Academic Press, 1970.
5) R.M.Alexander, "Elastic Mechanisms in Animal Movement", Cambridge University Press, 1988.

Name:
Junji Furusho

Affiliation:
Professor, Department of Computer-Controlled Mechanical systems,
Graduate school of Engineering, Osaka University

Address:
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

Brief Biographical History:
1976- Research Associate at Osaka University
1982- Associate Professor at Gifu University
1991- Professor at the University of Electro-Communications
1996- Professor at Osaka University

Main Works:
- His research interests include robotics
- Motion control of mechatronics systems
- Walking robots, haptic devices
- Rehabilitation training systems
- Mechatronics systems using intelligent fluids

Membership in Learned Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- The Society of Instrument and Control Engineers (SICE)
- The Virtual Reality Society of Japan (VRSJ)
- Society of Biomechanism Japan (SOBIM)
- The Institute of Electrical Engineers of Japan (IEEJ)

Name:
Masamichi Sakaguchi

Affiliation:
Assistant Professor, Department of Mechanical Engineering
Faculty of Engineering, Iwate University

Address:
4-3-5 Ueda, Morioka, Iwate 020-8551, Japan

Brief Biographical History:
1995- Joined the University of Electro-Communications
1996- Joined Osaka University
2001- Received the Ph .D. degree from Osaka University
2001- Joined Iwate University

Main Works:
- "Passive Force Display Using ER Brakes and its Control Experiments", Proc. IEEE Virtual Reality 2001 Conf., 7-12, Mar. (2001)
- "Basic Study on Rehabilitation Training System Using ER Actuators", Proc. IEEE Int. Conf. on Systems, Man, and Cybernetics, 135-140, Oct. (1999).
- "Development of DOF Force Display System Using ER Actuators", Proc. IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics, 707-712, Sep. (1999).

Membership in Learned Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- The Virtual Reality Society of Japan (VRSJ)
- The Society of Instrument and Control Engineers (SICE)
- Society of Biomechanisms Japan (SOBIM)

Name:
Naoyuki Takesue

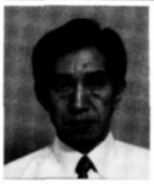
Affiliation:
Research Associate, Department of Computer-Controlled Mechanical Systems, Graduate School of Engineering, Osaka University

Address:
2-1 Yamadaoka, Suita, Osaka University

Brief Biographical History:
2000- Research Associate at Osaka University

Main Works:
- "Development and Analysis of Actuator with {ER} Damper", Proc. IEEE Int. Conf. on Robotics and Automation, 1328-1333, Apr. (2000)
- "High Stiffness Control of Direct-Drive Motor System by a Homogeneous ER Fluid", Proc. IEEE Int. Conf. on Robotics and Automation, 188-192, May. (1999).
- "Precise Positon Control of Robot Arms Using a Homogeneous ER Fluid", IEEE Control Systems Magazine, vol. 19, No.2, 55-61, Apr. (1999).

Membership in Learned Societies:
The Japan Society of Mechanical Engineers (JSME)
The Robotics Society of Japan (RSJ)
The Society of Instrument and Control Engineers (SICE)
The Institute of Electrical Engineers of Japan (IEEJ)
The Japan Society for Precision Engineering (JSPE)



Name:
Fuminobu Sato

Affiliation:
Senior Manager, Product Development Division, Mizuno Corporation

Address:
1-12-35 Nanko-kita, Suminoe-ku, Osaka, 559-8510, Japan

Brief Biographical History:
1972- Joined Mizuno Corporation

Name:
Takeshi Naruo

Affiliation:
Product Development Division, Mizuno Corporation

Address:
1-12-35 Nanko-kita, suminoe-ku, Osaka, 559-8510, Japan

Brief Biographical History:
1986- Joined Product Development Division, Mizuno Corporation

Name:
Hiroshi Nagao

Affiliation:
Product Development Division, Mizuno Corporation

Address:
1-12-35 Nanko-kita, Suminoe-ku, Osaka, 559-8510, Japan

Brief Biographical History:
1990- Joined Product Development Division, Mizuno Corporation